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THE HERBICIDAL PROPERTIES OF BORON COMPOUNDS[1]

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INTRODUCTION

IN THE FIELD of chemical weed control there is a constant demand for a reagent that will render the soil permanently sterile, for use on graveled driveways, parking areas, railroad right of ways, and similar areas where any plant growth is a nuisance. Although arsenic has proved most effective (*14*)[4] for this purpose, its use is always attended by a poison hazard. For this reason it seems desirable to find a soil sterilant that is nonpoisonous to man and animals. The known toxicity of boron compounds to plants suggests the possibility of their use for this purpose.

While it is recognized that toxic concentrations of boron occur in soils in certain regions in California and Nevada (*19, 23, 32*) and that the leaching of additional boron compounds into the underground waters in these regions is undesirable, there are large areas in these states, and others, where such a condition does not exist. In fact, as the data presented in this paper will show, one of the most promising uses for boron compounds is in the control of range weeds in the north-coast counties of California where the underground waters are not utilized for irrigation. It seems therefore that such materials may find extensive use in many places.

On the other hand, it is well to point out at the outset that wherever boron is present in toxic quantities in soils, and wherever crop plants may be affected, boron compounds should not be used in weed control. One of the principal objects of the work to be presented here was to determine the behavior of these substances in soils so that they might be

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[4] Italic numbers in parentheses refer to "Literature Cited" at the end of this paper.

handled with safety. From the results of the leaching studies, it is obvious that they would be useless, and possibly harmful, if applied below the water line in irrigation ditches and that they must be handled with caution on walks and drives beneath which the roots of trees and shrubs are growing. They should never be used in regions devoted to growing citrus and walnuts or even on range areas where the run-off contributes to the water supply of these regions. With these definite limitations in mind the studies that have been made are presented.

REVIEW OF LITERATURE

Although the toxic nature of boron compounds has been known since 1876 (*6*), relatively few attempts have been made to utilize them as herbicides. Thompson and Robbins (*37*), who tried borax and boric acid in their experiments on barberry eradication, did not consider them satisfactory. Other tests have been made (*12, 26*), but in no instance have boron compounds been recommended for use in weed control.

The literature on the toxicity of boron as a contaminating material in commercial fertilizers gives a different view. During the World War imports of potash from Germany were cut off, and a new supply had to be found. Among the sources were certain dry lakes in the desert regions of California. Salts extracted from these lake beds contained, besides potash and other elements, rather large percentages of borax. No great effort was made in the beginning to separate the borax completely from the potash; the possible effects of borax on plants were not fully realized.

As a consequence, serious crop injury resulted in certain of the eastern states, where large amounts of fertilizer are applied in the drill with the seed of such crops as cotton, corn, and potatoes. The injury having been traced to the borax present in the fertilizer, numerous investigations of the effect of borax on plants were conducted by state experiment stations and by the United States Department of Agriculture. The reports of these investigations give much valuable information on the toxic effects of boron compounds. This work will be summarized as it relates to the use of boron in weed control.

Boron as a Plant Poison.—Judging from tests on the relative toxicity of different compounds of boron (*6, 8, 38*), it is the borate ion that produces the injury; the various compounds, therefore, are toxic in proportion to the elemental boron they carry and are comparable on that basis. Even relatively insoluble compounds of boron are toxic (*20*) if available to the plants. From this we may conclude that the toxicity of these compounds is not related to any peculiarities of chemical combination or molecular structure as is the case with chlorates and thiocyanates; con-

sequently, boron compounds would not be subject to chemical decomposition that might tend to reduce their toxicity within the soil. Since the presence of boron in the soil solution in toxic quantities should render a soil sterile, the solubility of the compounds present will be the principal factor governing their effectiveness.

The highly toxic nature of boron is shown by many tests. Solution-culture experiments (*5, 6, 8, 20, 22, 27, 36, 38*) indicate that the lower limit of boron toxicity ranges from 1 to 10 parts per million, according to the plant species; and all cultures containing 1,000 p.p.m. or above were lethal.

Sand cultures (*6, 8*) showed critical concentrations of the same order but even lower lethal concentrations. Pot-culture tests with soils (*2, 3, 6, 8, 9, 11, 12, 20, 24, 38*) vary because of the different soil types used and the different methods of application. The critical concentrations, where they could be calculated, were in the neighborhood of 10 to 15 p.p.m. on the basis of the air-dry soil. Fifty p.p.m. definitely affected germination, and 100 p.p.m. prevented germination entirely.

Field trials reported (*6, 7, 10, 12, 29, 33, 35, 36, 38*) indicate wide differences in the susceptibility of plant species and also variations due to soil type, precipitation, and method of application. In most cases dosages of 200 pounds per acre or more of borax were lethal, and injury resulted when as little as 5 to 20 pounds was applied in the drill with the seed. In terms of elemental boron, 15 p.p.m. in the soil produced injury, and 400 p.p.m. was lethal.

The problem of the susceptibility of different cultivated plants to boron injury has received considerable attention (*4, 6, 7, 19, 20, 23, 25, 31, 32*). Scofield and Wilcox (*32*) group a number of crop plants according to their boron tolerance, using walnuts and citrus as standards. Eaton (*19*) lists 55 plants in the order of their boron tolerance. Obviously, wide differences exist in the ability of different species to tolerate boron in the soil. This factor must be considered in the use of any material for weed control; an application that fails to sterilize the soil completely is certain to cause a shift in the flora, the more tolerant species surviving. If these species are less desirable than the original mixed flora, then little or nothing is accomplished by the treatment.

Studies on the effects of the method of applying boron compounds show that the severest injury results from a concentration of the poison in the surface soil where the young absorbing roots come into direct contact with it (*34, 35*). A delay between fertilizer application and seeding, heavy rains immediately after application, or a thorough mixing of the chemical with a large mass of soil all tended to reduce boron toxicity.

These observations indicate that soluble boron compounds are leached from the soil and that they are rapidly rendered unavailable to plants upon contact with a large volume of soil. The effect of soil type upon availability of boron is also important in relation to the amount required to sterilize different soils. Previous studies on this problem (*9, 10, 18, 19, 27, 28, 32*) indicate that toxicity is greatest in coarse-textured soils. The results to be presented substantiate this conclusion and indicate the magnitude of the differences to be found.

As a number of workers (*3, 6, 7, 12, 13, 20, 35*) have observed, the toxic effects of an application of boron to the soil diminish appreciably with time. It seems evident not only that soluble boron compounds leach from the soil, as reported by Kelley and Brown (*23*), but that those remaining are gradually rendered unavailable to plants (*6*). Both these properties tend to reduce the effectiveness of boron as a soil sterilant, and they definitely limit the time that a given application will last.

The foregoing consideration of the work on boron toxicity shows why this material has not been recommended in weed control. Although very toxic to certain plants, it is much less harmful to others; it loses in potency soon after application, both by leaching and by fixation. Furthermore, it has not been promoted by any commercial agency and consequently has not been tried under a wide range of conditions.

With the proper criteria for judging the herbicidal value of a reagent and the necessary studies on its properties, it should be possible to find a place for so toxic a chemical as boron in a comprehensive program of weed control. Studies made within recent years on herbicides (*1, 14, 15, 16, 17, 21*) go far toward establishing the standards to be met by a weed killer. From their chemical nature it is evident that compounds of boron would find legitimate use only in the practice of soil sterilization where an agent nonpoisonous to man and animals is required. The studies reported herein show how closely these compounds meet the standards for such an agent.

GREENHOUSE STUDIES ON THE TOXICITY AND FIXING OF BORAX IN FOUR CALIFORNIA SOILS

Toxicity Studies.—Studies on the toxicity and fixing of borax were begun in the summer of 1933 and have continued for over two years. The present paper reports the results of a number of these. This work aimed to discover a possible use for boron compounds in the process of chemical soil sterilization and was therefore established on a basis almost diametrically opposed to that of others who have studied boron injury. Since it was hoped to make immediate and practical use of the informa-

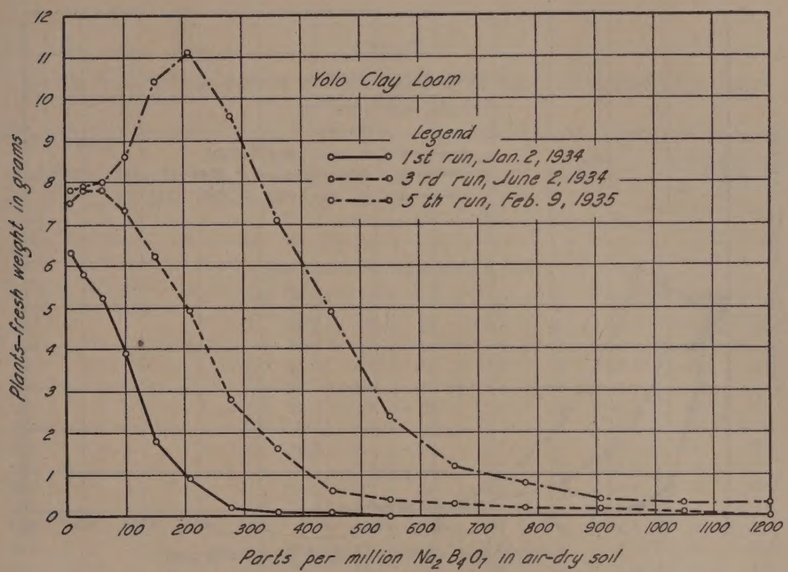

Fig. 1.—The relation of crop yield to the concentration of anhydrous borax in Yolo clay loam.

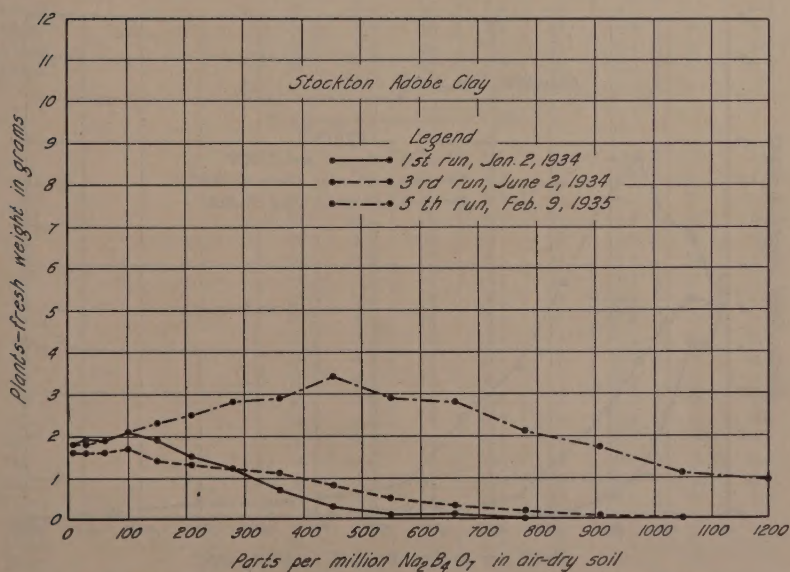

Fig. 2.—The relation of crop yield to the concentration of anhydrous borax in Stockton adobe clay.

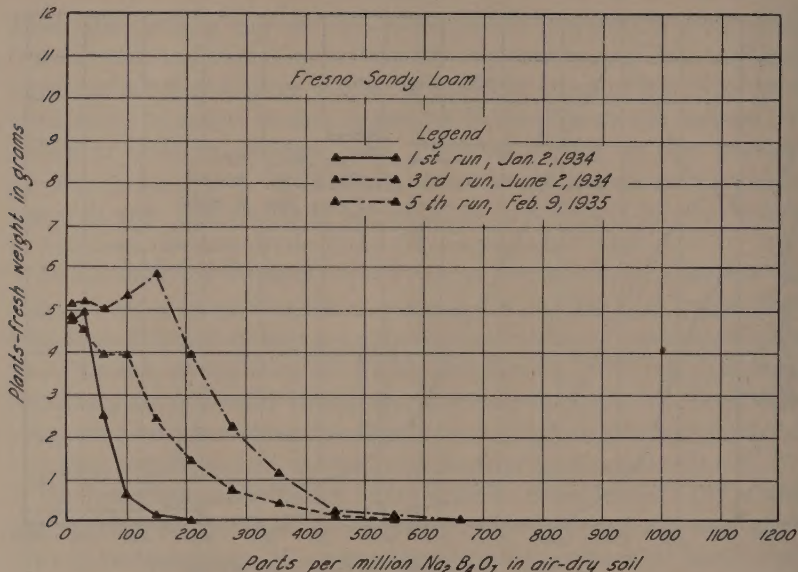

Fig. 3.—The relation of crop yield to the concentration of anhydrous borax in Fresno sandy loam.

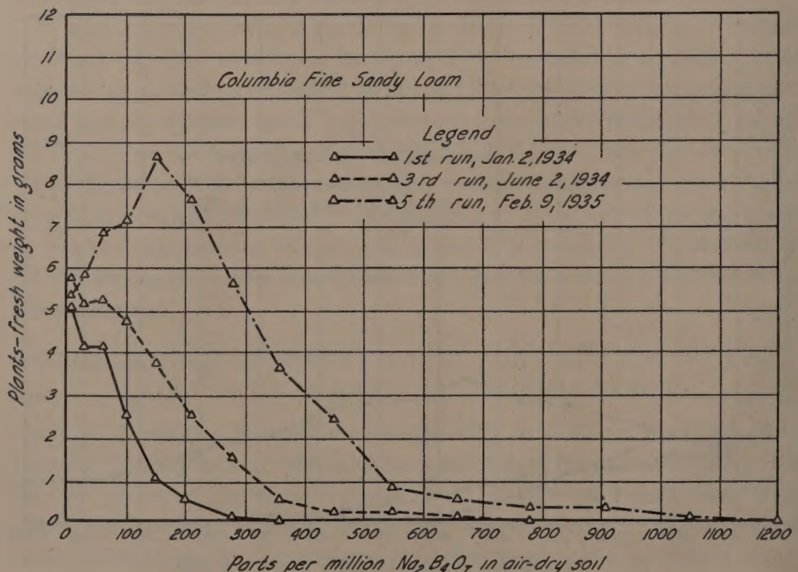

Fig. 4.—The relation of crop yield to the concentration of anhydrous borax in Columbia fine sandy loam.

TABLE 1

TOXICITY OF SODIUM BORATE IN FOUR CALIFORNIA SOILS, AS SHOWN BY GROWTH OF INDICATOR PLANTS

Sodium borate expressed as p.p.m. anhydrous borax in the air-dry soil	Yolo clay loam		Stockton adobe clay		Fresno sandy loam		Columbia fine sandy loam	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
First run, harvested January 2, 1934								
	cm	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
10	34	6.3	20	1.8	31	4.7	31	5.0
30	34	5.8	20	1.9	30	4.9	30	4.1
60	32	5.2	21	1.9	20	2.5	29	4.1
100	28	3.9	22	2.1	7	0.6	21	2.5
150	16	1.8	20	1.9	2	0.1	12	1.0
210	9	0.9	13	1.5	0	0.0	6	0.5
280	3	0.2	11	1.2	0	0.0	1	0.1
360	1	0.1	7	0.7	0	0.0	0	0.0
450	1	0.1	4	0.3	0	0.0	0	0.0
550	0	0.0	2	0.1	0	0.0	0	0.0
660	0	0.0	1	0.1	0	0.0	0	0.0
780	0	0.0	0	0.0	0	0.0	0	0.0
910	0	0.0	0	0.0	0	0.0	0	0.0
1050	0	0.0	0	0.0	0	0.0	0	0.0
1200	0	0.0	0	0.0	0	0.0	0	0.0
1360	0	0.0	0	0.0	0	0.0	0	0.0
Check	35	6.6	19	1.8	31	5.2	31	5.0
Check	34	6.3	20	2.0	31	5.2	31	4.9
Check	33	6.4	18	1.6	28	4.4	29	4.9
Check	32	6.3	19	1.7	31	5.2	26	4.7
Third run, harvested June 2, 1934								
	cm	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
10	35	9.7	21	2.9	26	4.3	31	7.0
30	37	10.1	22	3.0	28	4.1	32	6.3
60	39	10.1	22	3.0	27	3.5	33	6.4
100	39	9.5	23	3.1	26	3.5	34	5.8
150	36	8.0	22	2.5	24	2.2	31	4.5
210	33	6.4	22	2.3	16	1.2	27	3.1
280	27	3.6	23	2.2	13	0.6	21	1.8
360	24	2.1	22	2.0	10	0.4	15	0.6
450	15	0.8	19	1.4	7	0.1	10	0.3
550	14	0.5	17	0.8	0	0.0	8	0.2
660	12	0.3	11	0.5	0	0.0	7	0.1
780	10	0.2	10	0.3	0	0.0	0	0.0
910	10	0.2	8	0.2	0	0.0	0	0.0
1050	6	0.1	6	0.1	0	0.0	0	0.0
1200	0	0.0	0	0.0	0	0.0	0	0.0
1360	0	0.0	0	0.0	0	0.0	0	0.0
Check	33	8.2	23	3.4	25	4.3	29	6.2
Check	35	9.9	23	3.3	27	4.8	28	6.8
Check	29	7.7	20	3.2	25	4.0	29	5.7
Check	29	7.4	21	3.2	29	4.9	29	5.3

TABLE 1—*Concluded*

Sodium borate expressed as p.p.m. anhydrous borax in the air-dry soil	Yolo clay loam		Stockton adobe clay		Fresno sandy loam		Columbia fine sandy loam	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
Fifth run, harvested February 9, 1935								
	cm	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
10	28	4.6	15	1.6	22	2.8	23	3.6
30	29	4.7	15	1.6	23	2.8	25	3.9
60	29	4.7	15	1.6	23	2.7	28	4.5
100	31	5.1	16	1.8	24	2.9	30	5.0
150	33	6.2	17	2.0	27	3.1	34	5.7
210	35	6.6	19	2.2	24	2.1	34	5.1
280	34	5.7	21	2.5	17	1.2	31	3.7
360	32	4.2	23	2.5	13	0.6	25	2.4
450	28	2.9	24	3.0	7	0.2	22	1.6
550	20	1.4	22	2.5	5	0.1	13	0.5
660	13	0.7	22	2.4	0	0.0	10	0.5
780	11	0.5	18	1.9	0	0.0	7	0.2
910	8	0.2	16	1.5	0	0.0	6	0.2
1050	7	0.2	13	0.9	0	0.0	5	0.1
1200	7	0.2	12	0.8	0	0.0	0	0.0
1360	5	0.1	10	0.4	0	0.0	0	0.0
Check	26	4.0	15	1.7	23	2.7	24	3.7
Check	26	4.0	14	1.7	22	2.9	23	3.6
Check	23	3.4	14	1.4	21	2.6	21	2.8
Check	25	3.5	14	1.5	21	2.5	21	2.9

tion gained, a biological testing method was used which measured the toxicity of the applied chemical directly without resort to chemical analysis and subsequent interpretation. The results, therefore, are not so strictly quantitative as might be desired by some; but they have nevertheless provided valuable information and have aided greatly in the interpretation of field-plot data.

The method used has been described in a paper on the toxicity of sodium arsenite and sodium chlorate in California soils (*17*). Briefly, it consists of series of pot cultures grown in the greenhouse set up in No. 2 cans and containing increasing amounts of borax within each series. The soils used were Yolo clay loam, Stockton adobe clay, Fresno sandy loam, and Columbia fine sandy loam. Each culture in the Fresno sandy loam contained 600 grams of soil, and each in the other three soils contained 500 grams.

In making up the cultures the necessary amount of borax was applied, dissolved in a volume of water sufficient to bring the soil to field capacity. The actual moistening was done in three rapid stages so that the moisture was distributed within one minute or less. Previous tests with arsenic and chlorate had shown this to be a satisfactory method, giving a uniform distribution of the chemical.

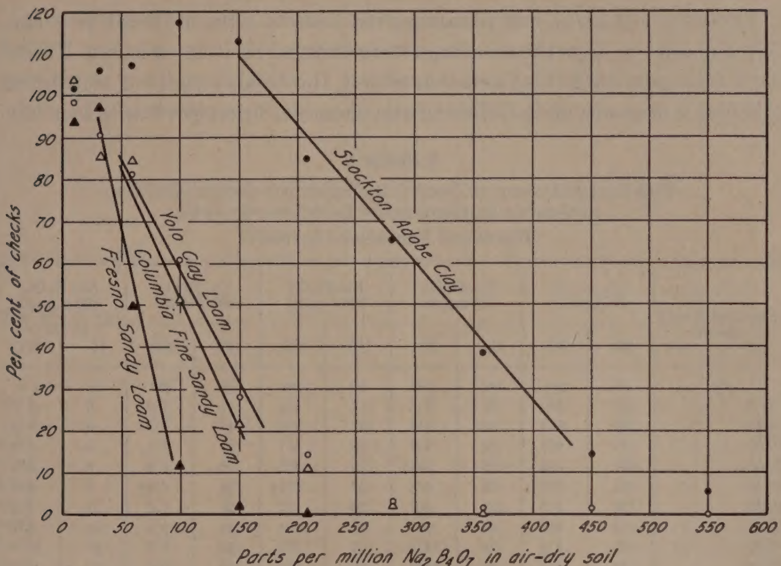

Fig. 5.—The relation of crop yield, expressed as per cent of the checks, to the concentration of anhydrous borax in four soils.

Fig. 6.—The relation of crop yield to penetration of borax into columns of four California soils, showing their power to retain this chemical.

The moistened soil was planted with Kanota oats, 13 seeds to a can. After about ten days the seedlings were thinned to 10 in each can. Thirty days from planting they were harvested, the fresh weight of tops being taken as a measure of the effect of the chemical upon growth. After harvest the tops were returned to the cans and were dried along with the soil for thirty days. The soils were then repulverized and returned to the cans, the dried tops being included under the soils. After moistening, the cultures were planted and carried along as in the first cropping. Five croppings are reported in this paper. The cultures are still on hand and will be cropped several more times. From the standpoint of weed control, the more important results are probably included in this report.

TABLE 2

THE FIXING POWER OF YOLO CLAY LOAM FOR SODIUM BORATE, AS SHOWN BY GROWTH OF INDICATOR PLANTS (Harvested December 15, 1934)*

Fraction of soil column	H_2O check		$Na_2B_4O_7$, 100 p.p.m.		$Na_2B_4O_7$, 200 p.p.m.		$Na_2B_4O_7$, 400 p.p.m.		$Na_2B_4O_7$, 800 p.p.m.	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0–9	24	5.9	28	5.2	24	4.3	11	1.0	0	0.0
9–18	24	5.9	26	5.4	27	4.7	17	1.8	0	0.0
18–27	24	6.7	27	5.9	26	4.7	17	1.4	0	0.0
27–36	24	6.3	24	5.9†	29	6.5	20	2.9	0	0.0
36–45	25	7.6	25	6.6	27	6.7†	28	5.9†	5	0.3
45–54	26	8.0	24	6.7	26	6.2	29	7.5	21	2.2
54–63	27	8.1	30	9.7	29	10.1	28	8.9	32	9.1†
63–72	27	9.2	28	11.4	27	9.6	28	8.6	27	10.4
72–81	26	8.7	28	11.2	28	9.5	30	10.7	27	8.7
81–90	24	7.0	28	7.8	24	7.4	25	7.7	27	8.2

Fraction of soil column	$Na_2B_4O_7$, 1,600 p.p.m.		$Na_2B_4O_7$, 3,200 p.p.m.		$Na_2B_4O_7$, 100 p.p.m.‡		$Na_2B_4O_7$, 400 p.p.m.‡		$Na_2B_4O_7$, 1,600 p.p.m.‡	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0–9	0	0.0	0	0.0	26	4.0	8	0.5	0	0.0
9–18	0	0.0	0	0.0	26	4.5	19	1.7	0	0.0
18–27	0	0.0	0	0.0	28	4.6	14	1.3	0	0.0
27–36	0	0.0	0	0.0	25	4.1†	19	2.1	0	0.0
36–45	0	0.0	0	0.0	27	4.6	24	3.8	0	0.0
45–54	0	0.0	0	0.0	21	3.2	24	4.0†	0	0.0
54–63	5	0.5	0	0.0	19	4.1	17	2.2	0	0.0
63–72	17	1.6	0	0.0	19	2.3	17	2.3	12	0.8
72–81	26	7.0†	21	2.7	19	3.0	18	2.9	21	2.4
81–90	25	6.1	21	5.4†	20	3.3	20	3.1	23	3.8†

* Average weight of plants in 10 untreated checks = 9.8 gm.

† Boron injury present to this depth.

‡ Soil in the last three columns moistened before the sodium borate was applied.

All cultures were replicated five times; and the points given in figures 1, 2, 3, and 4 on toxicity represent the average of the five. The figures mentioned present the data of the first, third, and fifth crops representative of the results on these soils; and table 1 gives the yields of these

TABLE 3

THE FIXING POWER OF STOCKTON ADOBE CLAY FOR SODIUM BORATE, AS SHOWN BY GROWTH OF INDICATOR PLANTS

(Harvested January 14, 1935)*

Fraction of soil column	H_2O check		$Na_2B_4O_7$, 100 p.p.m.		$Na_2B_4O_7$, 200 p.p.m.		$Na_2B_4O_7$, 400 p.p.m.		$Na_2B_4O_7$, 800 p.p.m.	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0– 9	14	1.1	14	1.1	14	1.3	11	1.1	0	0.0
9–18	13	1.0	14	1.0	14	1.1	12	1.3	3	0.1
18–27	13	1.0	13	0.9†	13	1.0	14	1.5	3	0.1
27–36	12	1.0	13	1.0	13	0.8†	13	1.2	4	0.2
36–45	13	1.1	12	1.0	14	1.1	13	0.9†	11	1.0
45–54	14	1.1	15	1.1	14	1.1	14	1.1	14	1.0†
54–63	14	1.1	14	1.2	14	1.2	12	0.9	14	1.1
63–72	15	1.3	17	1.9	15	1.3	16	1.4	16	1.5
72–81	16	1.6	16	1.6	19	2.0	16	1.6	18	2.2
81–90	16	1.6	17	1.8	17	1.8	17	1.5	18	1.5

Fraction of soil column	$Na_2B_4O_7$, 1,600 p.p.m.		$Na_2B_4O_7$, 3,200 p.p.m.		$Na_2B_4O_7$, 100 p.p.m.‡		$Na_2B_4O_7$, 400 p.p.m.‡		$Na_2B_4O_7$, 1,600 p.p.m.‡	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0– 9	0	0.0	0	0.0	17	1.4	16	1.5	0	0.0
9–18	0	0.0	0	0.0	15	1.0	14	1.4	0	0.0
18–27	0	0.0	0	0.0	14	1.1†	13	1.4	0	0.0
27–36	0	0.0	0	0.0	14	1.1	16	1.4	0	0.0
36–45	0	0.0	0	0.0	13	1.0	16	0.9†	0	0.0
45–54	12	1.2	0	0.0	14	1.1	15	1.0	8	0.3
54–63	14	1.0†	7	0.5	14	1.0	13	0.9	13	1.3
63–72	16	1.4	15	1.2	14	1.0	14	0.9	15	1.0†
72–81	18	2.0	15	1.6†	14	1.2	12	0.8	14	1.0
81–90	17	1.8	17	1.6	15	1.2	14	1.1	13	0.9

* Average weight of plants in 10 untreated checks = 1.5 gm.

† Boron injury present to this depth.

‡ Soil in the last three columns moistened before the sodium borate was applied.

crops. The relative toxicities in the four soils, and the loss of toxicity with time and cropping are shown. The curves for each soil have been reduced to a common base by multiplying values in the third and fifth runs by the average weight of first-run checks and dividing by the average weight of checks for the respective run.

In the coarser soils, evidently, borax is very toxic. The oat plant, being located at about the middle of the list of plants given by Eaton (*19*), is

intermediate in susceptibility to boron injury. The results of these tests show that boron, expressed as anhydrous borax, ranks in effectiveness with trivalent arsenic and sodium chlorate. The most pronounced difference occurs in Stockton adobe clay, where the toxicity of borax is notably low and the loss of toxicity with time and cropping very great. To study

TABLE 4

THE FIXING POWER OF FRESNO SANDY LOAM FOR SODIUM BORATE, AS SHOWN BY GROWTH OF INDICATOR PLANTS

(Harvested February 20, 1935)*

Fraction of soil column	H_2O check		$Na_2B_4O_7$, 100 p.p.m.		$Na_2B_4O_7$, 200 p.p.m.		$Na_2B_4O_7$, 400 p.p.m.		$Na_2B_4O_7$, 800 p.p.m.	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0– 9	26	2.9	25	2.3	24	2.5	18	1.4	3	0.1
9–18	23	3.2	23	2.6	25	2.5	22	1.9	10	0.5
18–27	25	3.0	26	2.9	26	2.8	21	1.8	8	0.3
27–36	25	3.2	26	2.9	27	3.0	26	2.3	8	0.3
36–45	26	3.4	26	3.2†	28	3.1	24	2.4	8	0.3
45–54	28	3.8	27	3.2	27	3.2	25	2.7	5	0.2
54–63	27	4.1	28	3.4	29	3.7	27	3.2	5	0.2
63–72	28	4.3	29	4.0	29	3.9†	29	3.7	9	0.4
72–81	31	6.2	31	4.5	31	5.6	31	5.3†	17	1.3†
81–90	33	7.6	36	6.9	35	7.5	34	7.4	33	6.8

Fraction of soil column	$Na_2B_4O_7$, 1,600 p.p.m.		$Na_2B_4O_7$, 3,200 p.p.m.		$Na_2B_4O_7$, 100 p.p.m.‡		$Na_2B_4O_7$, 400 p.p.m.‡		$Na_2B_4O_7$, 1,600 p.p.m.‡	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0– 9	0	0.0	0	0.0	26	2.3	19	1.4	0	0.0
9–18	0	0.0	0	0.0	23	2.2	24	2.2	0	0.0
18–27	0	0.0	0	0.0	23	2.1	22	1.8	0	0.0
27–36	0	0.0	0	0.0	25	2.4	22	2.1	0	0.0
36–45	0	0.0	0	0.0	25	2.7†	23	2.3	0	0.0
45–54	0	0.0	0	0.0	27	2.9	26	2.5	0	0.0
54–63	0	0.0	0	0.0	28	3.4	23	2.3	0	0.0
63–72	0	0.0	0	0.0	27	3.7	27	2.7	0	0.0
72–81	3	0.1†	0	0.0	22	3.0	23	2.0†	9	0.3
81–90	30	7.2	27	2.5†	23	2.9	23	2.4	23	2.3†

* Average weight of plants in 10 untreated checks = 4.8 gm.

† Boron injury present to this depth.

‡ Soil in the last three columns moistened before the sodium borate was applied.

the relation of toxicity and textural grade of the soil, the curves of the first runs have been reproduced, expressed on the basis of percentage of their checks. These curves appear in figure 5. Apparently a rough correlation exists between toxicity and particle size, as shown by the slopes of these curves. Considering the difference in the water-holding capacity of these soils, it seems that the differences in the three coarser

soils may be explained on the basis of differences in the concentration of borax in the soil solution. In the Stockton adobe clay, some other factor reduces the toxicity. This soil is highly colloidal but, under the conditions of this experiment, not particularly productive. Evidently it renders much of the applied borax unavailable to plants.

TABLE 5

THE FIXING POWER OF COLUMBIA FINE SANDY LOAM FOR SODIUM BORATE, AS SHOWN BY GROWTH OF INDICATOR PLANTS

(Harvested February 4, 1935)*

Fraction of soil column	H_2O check		$Na_2B_4O_7$, 100 p.p.m.		$Na_2B_4O_7$, 200 p.p.m.		$Na_2B_4O_7$, 400 p.p.m.		$Na_2B_4O_7$, 800 p.p.m.	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0– 9	16	2.1	16	1.9	18	1.9	4	0.2	0	0.0
9–18	16	2.1	17	2.2	14	1.4	10	0.8	0	0.0
18–27	16	2.7	16	2.1	13	1.2	12	0.9	0	0.0
27–36	16	2.4	17	2.3†	17	2.0	13	0.9	0	0.0
36–45	16	2.5	17	2.4	20	2.4†	16	1.4	2	0.1
45–54	16	2.4	17	3.0	17	2.9	19	2.3†	10	0.7
54–63	19	3.3	17	3.0	17	2.9	19	3.3	19	2.3†
63–72	24	4.7	23	4.3	24	4.4	24	4.9	25	4.8
72–81	28	6.9	27	6.8	28	7.2	28	6.7	28	6.3
81–90	27	6.1	28	7.0	26	5.4	26	6.3	26	5.7

Fraction of soil column	$Na_2B_4O_7$, 1,600 p.p.m.		$Na_2B_4O_7$, 3,200 p.p.m.		$Na_2B_4O_7$, 100 p.p.m.‡		$Na_2B_4O_7$, 400 p.p.m.‡		$Na_2B_4O_7$, 1,600 p.p.m.‡	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0– 9	0	0.0	0	0.0	14	1.5	6	0.4	0	0.0
9–18	0	0.0	0	0.0	14	1.4	9	0.7	0	0.0
18–27	0	0.0	0	0.0	15	1.6†	12	0.9	0	0.0
27–36	0	0.0	0	0.0	14	1.8	15	1.6	0	0.0
36–45	0	0.0	0	0.0	14	1.5	16	1.8	0	0.0
45–54	0	0.0	0	0.0	13	1.4	15	1.4	0	0.0
54–63	2	0.1	0	0.0	15	1.6	15	1.5	0	0.0
63–72	27	5.9†	0	0.0	15	1.8	15	1.6†	6	0.2
72–81	25	5.5	26	5.5†	15	1.5	15	1.9	11	0.9
81–90	27	5.4	28	6.0	18	2.0	16	1.8	17	1.6†

* Average weight of plants in 10 untreated checks = 6.5 gm.

† Boron injury present to this depth.

‡ Soil in the last three columns moistened before the sodium borate was applied.

Another interesting feature of these tests is the large loss of toxicity in the later runs. In every soil, by the fifth run, concentrations which had initially rendered the soil sterile have produced crops as good as the checks or better. In every soil also there is a noticeable stimulation of growth in the lower concentrations. After the harvest of the third run on June 2, 1934, the cultures stood in the greenhouse at Davis until Septem-

ber 18. During this time the loss of available borax was particularly noticeable.

Soil-Tube Studies.—To study the fixing or retention of borax in an available form by soils, tests were made using a special type of soil tube.

TABLE 6

RESULTS OF LEACHING SODIUM BORATE IN YOLO CLAY LOAM, AS SHOWN BY GROWTH OF INDICATOR PLANTS

(Harvested March 23, 1935)*

Fraction of soil column	Check		$Na_2B_4O_7$, 800 p.p.m.					
	10 cm H_2O		0 cm H_2O		2.5 cm H_2O		5.0 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0– 9	19	4.4	0	0.0	0	0.0	0	0.0
9–18	21	4.6	0	0.0	0	0.0	4	0.2
18–27	22	5.5	0	0.0	0	0.0	3	0.2
27–36	22	5.5	0	0.0	0	0.0	0	0.0
36–45	22	6.1	8	0.5	0	0.0	4	0.2
45–54	23	6.5	16	1.6	17	1.3	9	0.8
54–63	22	6.1	24	6.8†	23	4.8†	17	1.6
63–72	22	4.9	23	8.5	22	8.8	27	7.1†
72–81	22	4.7	21	8.7	29	10.1	26	9.3
81–90	19	4.3	22	8.0	25	9.5	24	7.3

Fraction of soil column	$Na_2B_4O_7$, 800 p.p.m.							
	10 cm H_2O		20 cm H_2O		40 cm H_2O		80 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0– 9	22	3.1	22	3.6	20	3.3	21	3.4
9–18	15	1.4	20	3.5	21	4.3	21	4.4
18–27	6	0.4	20	3.4	22	4.1	22	3.4‡
27–36	0	0.0	18	2.4	21	3.8	21	4.3
36–45	0	0.0	7	0.5	21	2.5	21	4.5
45–54	0	0.0	4	0.2	23	3.1	19	3.0
54–63	5	0.2	6	0.3	21	3.4	19	2.7
63–72	28	5.2	8	0.6	22	2.9	19	2.6
72–81	24	5.1†	18	1.8	11	0.7	20	2.7
81–90	22	5.0	18	2.2†	7	0.3†	20	2.9

* Average weight of plants in 10 untreated checks = 8.2 gm.
† Boron injury present to this depth.
‡ Boron injury present below this depth.

This consists of a sheet of celluloid bent to form a hollow cylinder. It is supported on the outside with a sheet of ½-inch-mesh hardware cloth bent around it and wired in place. The tube, filled with air-dry soil, is moistened slowly by dripping a given solution on the soil through a small glass jet. The jets are adjusted to deliver 12 drops per minute, and the tubes are usually moistened in 24 to 36 hours, according to the field

capacity of the soil being studied. The solutions used in these tests contained 100, 200, 400, 800, 1,600, and 3,200 p.p.m. anhydrous borax, respectively; and the same four soils were used. A check tube moistened with water was included in each set.

TABLE 7

RESULTS OF LEACHING SODIUM BORATE IN STOCKTON ADOBE CLAY, AS SHOWN BY GROWTH OF INDICATOR PLANTS

(Harvested April 22, 1935)*

Fraction of soil column	Check		$Na_2B_4O_7$, 800 p.p.m.					
	10 cm H_2O		0 cm H_2O		2.5 cm H_2O		5.0 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0– 9	16	1.7	9	0.2	10	0.5	20	1.3
9–18	16	2.0	10	0.3	8	0.4	10	0.7
18–27	16	1.7	12	0.5	8	0.4	6	0.3
27–36	16	1.8	19	1.2	7	0.6	8	0.4
36–45	18	2.2	18	1.1	18	1.0	12	0.8
45–54	19	2.1	19	1.5	19	1.2	18	1.2
54–63	18	2.2	16	1.4†	18	1.6	20	1.7
63–72	18	1.9	17	1.6	20	1.7†	17	1.9†
72–81	18	2.1	19	1.9	20	2.6	19	2.5
81–90	17	2.3	19	2.6	19	2.4	20	2.5

Fraction of soil column	$Na_2B_4O_7$, 800 p.p.m.							
	10 cm H_2O		20 cm H_2O		40 cm H_2O		80 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0– 9	15	1.0	16	1.4	17	1.7	15	1.8
9–18	18	1.1	15	1.3	15	1 4	14	1.5‡
18–27	11	0.5	16	1.2	16	1.5	13	1.4
27–36	12	0.7	16	1.1	17	1.4	14	1.2
36–45	12	0.7	16	1.2	18	1.3	16	1.5
45–54	14	0.9	18	1.4	17	1.3	16	1.2
54–63	19	1.3	19	1.5	19	1.2	19	1.4
63–72	19	1.6	17	1.2	19	1.2	20	1.3
72–81	19	2.3	19	1.5	17	1.2	19	1.2
81–90	17	2.1†	16	1.2†	16	1.0†	16	1.1

* Average weight of plants in 10 untreated checks = 1.8 gm.
† Boron injury present to this depth.
‡ Boron injury present below this depth.

After moistening, the tubes were allowed to stand for 48 hours to approach equilibrium. Then, while lying in a horizontal position, each tube was opened, the soil column divided into 10 fractions of equal length, and each fraction mixed and placed in a No. 2 can. These cultures were seeded and handled as were those of the previous experiments. Ten cans

of air-dry soil were moistened and seeded with each set of soil tubes. The average yield of these untreated checks is given at the foot of each table. The results of these tests are presented in tables 2, 3, 4, and 5. The more characteristic data are shown graphically in figure 6.

TABLE 8

RESULTS OF LEACHING SODIUM BORATE IN FRESNO SANDY LOAM, AS SHOWN BY GROWTH OF INDICATOR PLANTS (Harvested April 12, 1935)*

Fraction of soil column	Check		$Na_2B_4O_7$, 800 p.p.m.					
	10 cm H_2O		0 cm H_2O		2.5 cm H_2O		5.0 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0– 9	21	3.1	9	0.2	20	1.1	20	1.8
9–18	18	2.7	10	0.2	15	0.6	18	1.2
18–27	18	2.7	0	0.0	6	0.1	14	0.7
27–36	20	3.3	5	0.1	6	0.5	7	0.6
36–45	20	3.1	4	0.1	7	0.4	6	0.4
45–54	21	3.6	4	0.2	4	0.2	4	0.2
54–63	21	3.4	3	0.1	4	0.2	11	0.7
63–72	22	3.8	9	0.5	6	0.3	7	0.6
72–81	21	4.2	23	2.0†	10	0.9	8	0.8
81–90	22	3.2	25	4.7	14	1.0†	10	0.6†

Fraction of soil column	$Na_2B_4O_7$, 800 p.p.m.							
	10 cm H_2O		20 cm H_2O		40 cm H_2O		80 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0– 9	21	1.7	17	2.3‡	19	2.7	18	2.4
9–18	22	2.5	22	2.8	19	2.6	18	2.5
18–27	21	2.0	21	2.4	19	2.4	19	2.6
27–36	22	1.5	20	2.3	18	2.5‡	17	2.4
36–45	7	0.5	21	2.1	17	1.8	17	2.1
45–54	4	0.1	24	2.1	17	1.9	18	2.1
54–63	7	0.5	24	2.5	19	2.2	16	2.1
63–72	0	0.0	24	2.4	20	2.1	19	2.4
72–81	0	0.0	8	0.6	19	1.8	19	2.7
81–90	0	0.0†	10	0.5	22	2.4	23	2.9

* Average weight of plants in 10 untreated checks=5.4 gm.
† Boron injury present to this depth.
‡ Boron injury present below this depth.

Evidently, borax is held in the soil in an available form and tends to accumulate in the upper portion of the tube to which it is applied. Comparison with results of similar tests on sodium chlorate and sodium arsenite places borax between these other two chemicals in the firmness with which it is held.

As borax is somewhat less toxic than chlorate under the conditions of this experiment, the accumulation from the lower concentrations is less noticeable. In the higher concentrations, however, the results are more clear-cut. Probably the most outstanding difference occurs in the

TABLE 9

RESULTS OF LEACHING SODIUM BORATE IN COLUMBIA FINE SANDY LOAM, AS SHOWN BY GROWTH OF INDICATOR PLANTS (Harvested May 9, 1935)*

Fraction of soil column	Check		$Na_2B_4O_7$, 800 p.p.m.					
	10 cm H_2O		0 cm H_2O		2.5 cm H_2O		5.0 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0– 9	19	2.6	0	0.0	0	0.0	21	1.2
9–18	19	2.6	0	0.0	0	0.0	0	0.0
18–27	21	3.7	0	0.0	0	0.0	0	0.0
27–36	22	3.5	0	0.0	0	0.0	0	0.0
36–45	24	3.8	9	0.3	0	0.0	0	0.0
45–54	23	4.0	16	1.0	15	0.5	8	0.2
54–63	23	3.4	25	4.3	20	1.2	18	0.8
63–72	24	3.9	25	5.4†	26	5.1†	24	3.0†
72–81	26	5.2	30	8.9	29	6.8	30	7.6
81–90	28	6.7	28	8.0	28	6.1	27	7.7

Fraction of soil column	$Na_2B_4O_7$, 800 p.p.m.							
	10 cm H_2O		20 cm H_2O		40 cm H_2O		80 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0– 9	23	1.8	21	2.3	20	2.2	18	1.8
9–18	20	1.2	18	1.6	17	1.8	18	1.9
18–27	16	0.5	19	1.6	17	1.5	19	1.9
27–36	0	0.0	21	1.9	17	1.7	19	2.1‡
36–45	0	0.0	19	1.0	18	1.3	19	2.0
45–54	0	0.0	8	0.2	19	1.4	19	2.0
54–63	0	0.0	0	0.0	19	1.4	18	1.7
63–72	15	0.5	0	0.0	19	1.1	18	1.9
72–81	24	2.0†	0	0.0	13	0.4	21	2.0
81–90	29	6.3	9	0.2†	9	0.3†	19	1.9

* Average weight of plants in 10 untreated checks=8.9 gm.
† Boron injury present to this depth.
‡ Boron injury present below this depth.

Stockton adobe clay. Chlorate was not retained at a concentration above that of the moistening solution by this soil. Borax, on the other hand, is definitely accumulated in the upper fractions from the three more concentrated solutions. As with arsenic, the quantity held (at least in this one soil) was greater with the higher concentrations of the moistening solutions.

Leaching Studies.—The effect of leaching upon the movement of borax within the soil columns is shown in the next set of experiments. In these tubes the initial moistening solution contained 800 p.p.m. of anhydrous borax. Seven tubes of each soil were moistened with this solution; an eighth tube was moistened with distilled water as a check. After moistening, the tubes were leached with different volumes of distilled water expressed in the tables as surface centimeters, and, after standing 48

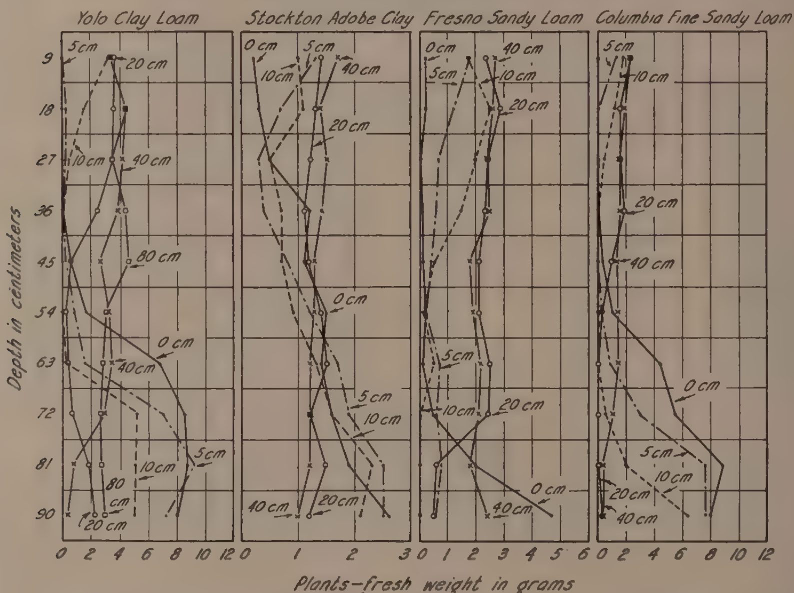

Fig. 7.—The effect of leaching upon the location of borax in soil columns as shown by crop yield.

hours, were divided into ten fractions, planted, and handled as in the previous experiments.

The data on these tests are presented in tables 6, 7, 8, and 9 and shown in the form of curves in figure 7. Comparison with the results obtained with chlorate and arsenic (*17*) indicate again that the borax is more firmly held than the former and less firmly than the latter. In the Yolo soil, borax was present in toxic amounts in the lower fractions of the column leached with 80 cm of water.

In the Stockton adobe clay the low toxicity of borax somewhat obscures the effects of leaching. The results would have been more clear-cut had the moistening solution contained more borax. Nevertheless, the chemical tended to remain in the top of the column and was reduced in

concentration below the limits of visible toxicity by the increased leaching instead of being displaced toward the bottom of the tube as in the other soils.

In the coarser soils the borax was readily displaced by leaching, the columns being left relatively free of chemical by the larger volumes of water.

The range of concentrations in the soil that can be tested by this method is very definitely limited by the sensitivity of the indicator plant used. Not only is the range limited, but it varies with the different soils and with the time elapsed between application and the growth of the crop. For these reasons chemical studies are needed to substantiate and extend these results. Analyses of these treated soils should give a much more accurate picture of the concentrations and the distribution of borax under the different experimental conditions.

PLOT TESTS WITH BORON COMPOUNDS

Davis Plots.—As shown by the toxicity tests reported, borax is a very toxic chemical on many soils, ranking with sodium chlorate and sodium arsenite in its ability to render the soil sterile immediately after application. It loses its toxicity rather rapidly, however, under the conditions of plant growth and, furthermore, is not firmly held in available form in the coarser soils in which it is most toxic. It is likely, therefore, to have only a limited usefulness in weed control, being effective on light soils in regions of low rainfall or upon plants especially susceptible to boron injury.

The first plots to be treated with boron compounds at Davis were established in the winter of 1933–34. They were located on the banks of an abandoned irrigation ditch on a Yolo fine sandy loam. A mixed growth of grasses and various winter annuals covered the soil at the time the applications were made. The plots were each 1 square rod in area and were treated with a number of chemicals, including borax in solution, borax in combination with sodium arsenite in solution, dry powdered borax, and mixtures of dry borax and arsenic trioxide. A few plots received colemanite, a mixed borate of sodium and calcium, somewhat less soluble than borax; others received colemanite with dry arsenic trioxide. Two plots were treated with a mixture of colemanite and sodium chlorate. The results on these plots, shown in table 10, are visual estimates of the surviving plants at the dates indicated. Check plots with arsenic and chlorate alone (*14*) were included, but are not reported in the table.

Evidently straight borax either dry or in solution is much less toxic in the field than sodium chlorate or arsenic. When mixed with arsenic,

TABLE 10

Effects of Various Soil Sterilants Upon Weed Growth; Plots at Davis
(Applications made in December, 1933, and January, 1934)

Plot No.	Chemicals applied, pounds per square rod				Per cent weed stand on dates given		
	Chemical	Dosage	Chemical	Dosage	April 5, 1934	July 16, 1934	April 12, 1935
1	Borax in solution	2	....	..	90	90	100
2	Borax in solution	3	....	..	80	90	100
3	Borax in solution	4	....	..	30	80	100
4	Borax in solution	8	....	..	40	80	95
5	Borax in solution	12	....	..	7	15	30
6	Borax in solution	1	Sodium acid arsenite in solution expressed in terms of As_2O_3	4	30	70	90
7	Borax in solution	2	Sodium acid arsenite in solution expressed in terms of As_2O_3	4	25	60	90
8	Borax in solution	3	Sodium acid arsenite in solution expressed in terms of As_2O_3	4	2	10	60
9	Borax in solution	1	Sodium acid arsenite in solution expressed in terms of As_2O_3	6	10	20	90
10	Borax in solution	2	Sodium acid arsenite in solution expressed in terms of As_2O_3	6	15	40	75
11	Borax in solution	3	Sodium acid arsenite in solution expressed in terms of As_2O_3	6	10	20	90
12	Borax in solution	1	Sodium acid arsenite in solution expressed in terms of As_2O_3	8	2	5	40
13	Borax in solution	2	Sodium acid arsenite in solution expressed in terms of As_2O_3	8	7	10	25
14	Borax in solution	3	Sodium acid arsenite in solution expressed in terms of As_2O_3	8	1	5	10
15	Borax, dry	2	....	..	100	100	100
16	Borax, dry	4	....	..	100	100	100
17	Borax, dry	6	....	..	100	100	100
18	Borax, dry	8	....	..	60	75	90
19	Borax, dry	10	....	..	40	40	90
20	Borax, dry	12	....	..	10	10	30
21	Borax, dry	2	Arsenic trioxide, dry	4	90	90	10
22	Borax, dry	4	Arsenic trioxide, dry	4	90	100	15
23	Borax, dry	6	Arsenic trioxide, dry	4	20	40	5
24	Borax, dry	2	Arsenic trioxide, dry	6	90	100	20
25	Borax, dry	4	Arsenic trioxide, dry	6	30	45	2
26	Borax, dry	6	Arsenic trioxide, dry	6	40	50	1
27	Borax, dry	2	Arsenic trioxide, dry	8	40	50	1
28	Borax, dry	4	Arsenic trioxide, dry	8	50	90	2
29	Borax, dry	6	Arsenic trioxide, dry	8	10	15	1
30	Colemanite, dry	4	....	..	100	100	100
31	Colemanite, dry	6	....	..	100	100	90
32	Colemanite, dry	8	....	..	100	100	100
33	Colemanite, dry	12	....	..	75	90	60
34	Colemanite, dry	2	Arsenic trioxide, dry	4	100	100	90
35	Colemanite, dry	4	Arsenic trioxide, dry	4	100	100	20
36	Colemanite, dry	6	Arsenic trioxide, dry	4	100	100	5
37	Colemanite, dry	8	Arsenic trioxide, dry	4	75	75	5
38	Colemanite, dry	12	Arsenic trioxide, dry	4	75	100	10
39	Colemanite, dry	4	Sodium chlorate, dry	1	25	50	100
40	Colemanite, dry	8	Sodium chlorate, dry	1	2	10	50

furthermore, the borax added little or nothing to the effectiveness of the treatment. In the case of the dry mixtures with arsenic the treatments were more effective the second year, probably because of a slow dissolving of the arsenic and retention in an available form in the top soil. The borax failed to improve the results of this type of application.

Arsenic, either in the form of sodium arsenite or as the dry trioxide, is very effective in soil sterilization. Its principal drawback is its poisonous nature. Sodium chlorate, though also effective, is costly, is hazardous to handle, and rapidly loses its toxicity by decomposition and leaching. For these reasons boron compounds would be preferable if they were more effective.

Probably the most promising result obtained the first season was that of the colemanite-chlorate plots listed at the bottom of table 10. These plots were relatively free of vegetation throughout the first winter and spring and for much of the second winter. The mixture of one pound of sodium chlorate with 8 pounds of colemanite would be relatively low in cost, nonpoisonous, and practically free of fire hazard.

The second season's plots were treated to test the relative effectiveness of the borate-chlorate mixtures. A portion of the same abandoned ditch was used, and applications were made in December, 1934. Results on these plots are shown in table 11.

The total seasonal rainfall during the winter of 1934–35 was 18.71 inches. At the time of application in December, 1934, 4.94 inches had fallen, leaving a difference of 13.77 inches received by the plots, much of which came in March and April. These heavy spring rains explain to a certain extent the poor results on these plots. Plots with only a scattering of weak chlorotic plants in early March later developed a fairly heavy growth. Experience indicates that the applications would have been far more effective had the spring been dry.

On the other hand, the boron compounds used in these experiments were not nearly so effective as the greenhouse results would seem to promise. Only when mixed with sodium chlorate were they satisfactory. The colemanite mixtures gave the best results under conditions at Davis.

During this same season a number of applications were made on different areas on the University Farm in an attempt to control miscellaneous weeds. These trials were made on fence lines, roadsides, graveled parking areas, graveled walks, and other places usually hoed during the spring. Most of the applications were light—from 1 to 4 pounds per square rod. Some of the treatments were repeated several times as weed growth seemed to warrant.

As the season advanced it became very evident that the treatments

TABLE 11

EFFECTS OF CHLORATE-BORATE MIXTURES UPON WEED GROWTH; PLOTS AT DAVIS
(Applications made in December, 1934)

Plot No.	Chemicals applied, pounds per square rod				Per cent weed stand on dates given	
	Chemical	Dosage	Chemical	Dosage	April 12, 1935	October 5, 1935*
1	Borax, dry	2	Sodium chlorate	½	70	90
2		4		1	60	80
3		6		1½	50	70
4		8		2	15	50
5		4		½	60	90
6		8		1	50	75
7		12		1½	20	40
8		16		2	10	20
9	Borax, dry	4	....	...	100	100
10		8	....	...	100	100
11		12	....	...	90	100
12		16	....	...	80	100
13	Kramer ore, dry	2	Sodium chlorate	½	80	100
14		4		1	70	90
15		6		1½	60	90
16		8		2	40	75
17		4		½	75	100
18		8		1	35	70
19		12		1½	25	50
20		16		2	15	30
21	Kramer ore, dry	4	....	...	100	100
22		8	....	...	100	100
23		12	....	...	100	100
24		16	....	...	100	100
25	Colemanite, dry	2	Sodium chlorate	½	75	100
26		4		1	30	100
27		6		1½	15	90
28		8		2	5	75
29		4		½	50	100
30		8		1	15	100
31		12		1½	5	90
32		16		2	0	50
33	Colemanite, dry	4	....	...	100	100
34		8	....	...	100	100
35		12	....	...	100	100
36		16	....	...	100	100
37	....	..	Sodium chlorate	½	80†	100†
38	....	..		1	70†	100†
39	....	..		1½	60†	90†
40	....	..		2	60†	90†

* Winter and spring annuals on these plots were mature at the time the data were taken in April. The difference in stand in October was due to a growth of *Kickxia elatine*, a prostrate summer annual with a high salt tolerance.

† Average of 2 plots.

where two or three light applications were made were much more satisfactory than those in which the total dose was applied at one time.

Considering all of the results so far obtained with boron compounds in soil sterilization, on the fertile alluvial soils of the interior valleys of California colemanite appears to be the most effective material. Mixed with sodium chlorate at a rate of 8 parts to 1 by weight, it makes an effective sterilant if properly used. The above-mentioned experiments indicate that several light applications of the mixture through the season as the weed growth warrants are more effective than one heavy application of a like total amount. Graveled areas yield much more satisfactory results than bare soil. Dosages must be far heavier under the latter conditions. Results of using the mixture on deep-rooted perennials do not differ from those obtained by applying the chlorate which it contains alone. Borates applied to the top soil have no effect below the top few inches upon such weeds as morning-glory and creeping mallow.

Humboldt County Plots.—The results obtained with boron compounds in the control of Klamath weed on the more heavily leached soils of Humboldt County differ considerably from those that have just been presented.

Klamath weed (*Hypericum perforatum*), a weed pest on range lands in parts of northern California (*30*), is a perennial with a root system that may extend to a depth of 3 feet. It has no feed value and frequently grows in stands so dense as to crowd out desirable plants.

Experimental plot studies with soil sterilants in stands of Klamath weed in southern Humboldt County have been carried on for the past year and a half. The soil sterilants include borax, colemanite, Kramer ore (a crude sodium borate), and mixtures of these with sodium chlorate, sodium arsenite, and arsenic trioxide.

The first applications of borax and mixtures of borax with other chemicals were made near Blocksburg in March, 1934. Rainfall amounting to 8.86 inches fell between the date of application and July 1, the end of the season. These plots now have also had the 1934–35 season's rainfall of 49.23 inches—a total of 58.09 inches up to July 1, 1935. Results on these plots are given in table 12, expressed in terms of percentage stand of Klamath weed surviving the treatment. The field in which these plots are located had practically a solid stand of Klamath weed, with a small percentage of annual grasses. Removal of Klamath weed by mechanical means or by temporary soil sterilants usually results in a dense stand of annual grasses in the second year. Very little grass grew on any of the borax plots during the spring and summer of 1934. By the summer of 1935 some grass and annual weeds appeared on all plots

TABLE 12

EFFECTS OF VARIOUS CHEMICALS UPON KLAMATH WEED; SOIL STERILIZATION PLOTS AT BLOCKSBURG

(Applications made in March, 1934)

Plot No.	Chemicals applied, pounds per square rod				Per cent weed stand on dates given		
	Chemical	Dosage	Chemical	Dosage	May 8, 1934	August 15, 1934	May 2, 1935
1	Borax, dry	2	....	..	100	90	70
2		4	....	..	75	70	50
3		6	....	..	60	60	40
4		8	....	..	50	60	25
5		12	....	..	25	15	10
6	Borax, dry	2	Arsenic trioxide, dry	4	100	80	75
7		4		4	100	90	90
8		6		4	40	30	40
9		2		8	90	70	80
10		4		8	75	75	40
11		6		8	35	40	25
12		2		12	75	40	25
13		4		12	50	25	20
14		6		12	50	30	70
15	Borax, dry	4	Sodium chlorate, dry	1	25	2	5
16		4		2	25	2	3
17		4		3	20	1	1
18		8		1	10	3	5
19		8		2	5	1	1
20		8		3	5	1	0
21		12		1	3	1	1
22		12		2	3	0	0
23		12		3	2	0	0
24	....	..	Sodium chlorate, dry	1	75	60	40
25	....	..		2	60	100	100
26	....	..		3	30	40	50
27	....	..		4	10	3	5
28	....	..		6	10	1	0
29	Borax in solution	1	Sodium acid arsenite in solution expressed in terms of As_2O_3	4	10	25	35
30		2		4	10	15	25
31		1		6	5	20	60
32		2		6	3	5	25
33		1		8	0	1	1
34		2		8	0	1	1
35	....	..	Sodium acid arsenite in solution	4	10	25	30
36	....	..		6	1	5	20
37	....	..		8	1	5	15

except those treated with arsenic trioxide and sodium arsenite. All borax-treated plots had a reduced stand of grasses. Four pounds of borax per square rod reduced the stand of grasses and annual weeds by about 50 per cent; 8 pounds, by about 75 per cent.

Of this series of treatments, the mixtures of borax and sodium chlorate were the most effective against Klamath weed. The mixture of 4 pounds borax and 1 pound sodium chlorate per square rod gave satisfactory control.

The mixtures of borax with arsenic trioxide and sodium arsenite gave results no better than those of the arsenic compounds applied alone.

Another set of plots was laid out in another field in the same general locality and treated during the winter of 1934–35. Conditions of soil, topography, and plant cover were similar in the two fields. Each treatment was repeated several times between November, 1934, and April, 1935. The results of these treatments are reported in table 13. The results as stated are for Klamath weed only.

Best results with borax, both dry and in solution, were obtained from applications made about February 1. These applications had 16.22 inches of rain up to the end of the season. Eight pounds per square rod gave satisfactory control of Klamath weed under these conditions.

The dry borax-chlorate mixtures were most effective in the March 30 application. The rainfall between that date and the end of the season was 7.68 inches. This is not far from the 8.86 inches received by the series of plots treated the previous March, and the results are equally satisfactory. Again the combination treatment gave better results than either of the ingredients applied alone.

In general, results of treatments combining sodium chlorate and borax in solution are of the same order as for the corresponding dry treatments. None of the solution applications received the amount of rainfall that proved to be optimum for the dry treatments. The February 9 applications had 16.64 inches; the April 22 application but 0.84.

The November and April applications of colemanite and Kramer ore gave better results than the corresponding dry-borax treatments; but the January and February applications were not as effective as the corresponding borax application.

Combinations of colemanite with sodium chlorate, and Kramer ore with sodium chlorate were better than the corresponding combinations of sodium chlorate and borax applied on the same dates, and in general the Kramer-ore combinations appeared better than those with colemanite, though the differences may not be significant. Unfortunately, no colemanite or Kramer-ore combinations were applied on March 30,

TABLE 13

EFFECTS OF VARIOUS CHEMICALS UPON KLAMATH WEED; SOIL STERILIZATION PLOTS AT CASTERLIN, 1934–35

Plot No.	Chemicals applied, pounds per square rod: Chemical	Dosage	Chemical	Dosage	Per cent weed stand observed on Sept. 10, 1935, from applications made on dates given					
					Nov. 15	Dec. 8	Jan. 30	Feb. 2	Mar. 30	April 11
1	Borax, dry	4	....	..	100	50	40	20	40	80
2		8	....	..	100	40	10	1	30	50
3		12	....	..	90	20	1	1	30	50
4		16	....	..	80	15	0	1	25	50
5		20	....	..	30	10	0	5	15	60
					Nov. 22	Dec. 7	Feb. 4	Feb. 9	April 18	
6	Borax in solution	2	....	..	50	100	80	40	60	..
7		4	....	..	30	80	60	60	60	..
8		6	....	..	30	60	15	2	60	..
9		8	....	..	20	40	1	40	40	..
10		12	....	..	10	25	0	50	30	..
11		16	....	..	1	10	0	..	..	..
					Nov. 15	Dec. 9	Jan. 30	Feb. 2	Mar. 30	April 12
12	Borax, dry	2	Sodium chlorate, dry	1	100	25	..	..	..	..
13		2		2	100	25	..	..	..	..
14		4		1	100	40	40	50	2	80
15		4		2	70	40	50	60	2	70
16		6		1	..	..	25	40	8	50
17		6		2	..	..	20	60	3	20
18		8		1	65	50	10	60	3	50
19		8		2	40	30	10	50	3	40
					Nov. 25	Dec. 7	Feb. 5	Feb. 9	April 22	
20	Borax in solution	2	Sodium chlorate in solution	1	15	40	100	..	..	..
21		2		2	15	30	90	..	..	..
22		4		1	10	30	60	75	70	..
23		4		2	5	25	30	90	70	..
24		6		1	..	..	25	70	50	..
25		6		2	..	..	30	50	15	..
26		8		1	0	40	..	30	40	..
27		8		2	0	20	..	30	15	..
					Nov. 15	Dec. 8	Jan. 30	Feb. 2	Mar. 30	April 11
28	....	..	Sodium chlorate, dry	1	80	30	100	20	10	40
29	....	..		2	75	25	80	40	15	40
30	....	..		3	80	25	60	40	10	40
31	....	..		4	70	20	60	50	3	40
32	....	..		6	75	15	25	20	2	10

TABLE 13—*Concluded*

Plot No.	Chemicals applied, pounds per square rod				Per cent weed stand observed on Sept. 10, 1935, from applications made on dates given					
	Chemical	Dosage	Chemical	Dosage						
					Nov. 22	Dec. 7	Feb. 4	Feb. 9	April 18	
33	....	..	Sodium chlorate in solution	1	50	100	25	50	75	..
34	....	..		2	70	70	30	35	50	..
35	....	..		3	40	60	40	40	20	..
36	....	..		4	20	40	40	40	15	..
37	....	..		6	5	50	40	50	20	..
					Nov. 20	Feb. 3	April 11			
38	Colemanite, dry	4	....	..	80	90	70	..	..	..
39		8	....	..	80	50	15	..	..	..
40		12	....	..	80	20	15	..	..	..
41		16	....	..	30	2	15	..	..	..
42		20	....	..	30	5	10	..	..	..
					Nov. 20	Feb. 3	April 11			
43	Kramer ore, dry	4	....	..	70	50	40	..	..	..
44		8	....	..	70	40	15	..	..	..
45		12	....	..	30	10	15	..	..	..
46		16	....	..	5	2	10	..	..	..
47		20	....	..	5	20	10	..	..	..
					Nov. 20	Feb. 3	April 17			
48	Colemanite, dry	2	Sodium chlorate, dry	1	75	..	..	..	..	..
49		2		2	75	..	..	..	..	..
50		4		1	80	30	15	..	..	..
51		4		2	35	50	5	..	..	..
52		6		1	..	60	5	..	..	..
53		6		2	..	50	5	..	..	..
54		8		1	50	50	8	..	..	..
55		8		2	30	40	3	..	..	..
					Nov. 20	Feb. 3	April 18			
56	Kramer ore, dry	2	Sodium chlorate, dry	1	70	..	..	..	..	..
57		2		2	50	..	..	..	..	..
58		4		1	50	15	10	..	..	..
59		4		2	30	60	5	..	..	..
60		6		1	..	30	8	..	..	..
61		6		2	..	30	5	..	..	..
62		8		1	50	15	3	..	..	..
63		8		2	50	10	2	..	..	..

the date that gave the best results with the borax combinations. The applications of April 17 and 18 received but 0.84 inch of rain; and though the results are significantly better than from the ores alone or chlorate alone, the treatments would probably have been still more effective had they received more rainfall.

DISCUSSION AND SUMMARY

Although boron compounds are extremely toxic to some plants and may reduce growth and produce characteristic symptoms when present in relatively low concentrations in the soil, in chemical weed control they will find only limited use. The high toxicity indicated in the greenhouse tests is less evident in the field. These compounds, furthermore, are not retained in the soil against the leaching power of moving water to the same extent as arsenic. For complete sterilization, in consequence, dosages must be heavy and applications frequent. The discrepancy between the toxicity expressed in the greenhouse tests and that observed on field plots seems somewhat anomalous until one considers the time effect. As shown by figures 1, 2, 3, and 4, borax loses rapidly in toxicity when held in a given mass of soil. In the field this action is superimposed on the effects of the loss by leaching from the surface soil, and together these losses reduce the effective concentration until seedlings are permitted to develop. When these seedlings are of a tolerant species they grow, and the plots become reinfested. Evidently, therefore, the use of boron in soil sterilization will be limited both by the species existent on the areas and by the amount and distribution of the seasonal rains.

The results on the Davis plots are given in terms of the effects of boron compounds upon growth of the common winter annuals of that region. Most of these plants, adapted to growing in regions of medium to low rainfall, thrive in soils containing a fairly high level of soluble salts. They are all fairly tolerant of boron, and relatively high concentrations in the soil solution are required to kill them. Klamath weed (*Hypericum perforatum*), a native of northern Europe, grows only in regions of medium to high rainfall, where soils are heavily leached and contain relatively little soluble material. Klamath weed, therefore, is injured by high concentrations of salts in the soil solution and is highly susceptible to boron poisoning. Therefore boron compounds should be useful in controlling Klamath weed, especially when combined with sodium chlorate to increase the toxicity. Their low solubility should result in some residual effect, reducing the probability of reinfestation by seedlings. Their nonpoisonous and fire-deterrent properties should appreciably reduce the hazard over that of sodium chlorate or arsenic.

Against more tolerant plants and in regions of fertile, recent alluvial soils the use of boron compounds seems limited to the coarser soils or to graveled areas; and where rainfall exceeds 10 inches annually, applications will be needed one or more times each year.

Again it should be emphasized that boron compounds must be used with caution close to ornamental plants, around orchards or groves of such susceptible species as citrus and walnuts, and in regions where there is a possibility of contamination of water supplies used for irrigation.

With these obvious drawbacks, however, the combination of sodium chlorate with some one of the cheap boron ores should find wide use in such places as school grounds, parking areas, airports, and graveled walks and driveways, where a nonpoisonous soil sterilant is desirable.

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SOME EFFECTS OF THALLIUM SULFATE UPON SOILS

A. S. CRAFTS

SOME EFFECTS OF THALLIUM SULFATE UPON SOILS[1,2]

A. S. CRAFTS[3]

INTRODUCTION

WITH THE INCREASING USE of poisons for pest control in agriculture, new and little-known chemicals are frequently introduced. The ultimate effects of these reagents upon soils and crops may present serious problems, and the continued use of certain of them cannot be safely recommended until their long-time behavior is understood.

Brooks (*1*)[4] has warned of the possible sterilization effects of thallium sulfate used in rodent control, and McCool (*4*) has confirmed the highly toxic nature of this chemical in soils.

In pest control, toxicity is of eminent importance; and in weed work, soil effects are of special interest. Although thallium compounds are too expensive to be practical in weed control, their behavior in soils characterizes a certain type of toxic materials. A study of their reactions should contribute to our general information.

A preliminary report on work done on the problem of thallium toxicity in California soils has been published (*2*). The method used in toxicity studies, as already described by the author (*3*) in a previous paper, consists principally in pot-culture tests using 500-gram lots of soils in No. 2 cans as the culture media. The chemicals to be tested are applied to the soils in various ways, and their effects upon indicator plants (Kanota oats) are measured by recording height and fresh weight of the latter after a 30-day growth period. The details of the individual tests with thallium will become apparent in the following pages.

[1] Received for publication May 8, 1936.

[2] This investigation was undertaken at the request of a special committee appointed in the University of California in 1932 to study problems involved in rodent and wild-life control. The use of chemicals, including thallium sulfate, for rodent control was studied by this committee. Certain claims had been made as to the possible or probable sterilizing effect of thallium salts if distributed in connection with rodent control. The literature then available did not provide satisfactory answers to these claims. The Division of Botany of the College of Agriculture was asked by the committee to conduct a study of the effect of thallium sulfate on soils. Dr. T. I. Storer of the Zoölogy Division of the College of Agriculture, who was a member of the above committee, coöperated in the planning and execution of the experiments. The paper presented herewith incorporates the results of this study. Dr. Crafts found, however, that certain general principles with respect to the effect of salts of heavy metals on soils could be elucidated by use of thallium sulfate, and the studies were therefore carried farther than necessary to provide an answer to the original request.—C. B. Hutchison, Director of the Agricultural Experiment Station.

[3] Assistant Professor of Botany and Assistant Botanist in the Experiment Station.

[4] Italic numbers in parentheses refer to "Literature Cited" at the end of this paper.

EXPERIMENTS

Toxicity Studies.—Two toxicity series have been run with thallium sulfate. The first, a short concentration series in Yolo clay loam, having been cropped twelve times, gives a picture of the effects of time and re-

TABLE 1

TOXICITY OF THALLIUM SULFATE UPON SUCCEEDING CROPS IN YOLO CLAY LOAM, AS SHOWN BY GROWTH OF INDICATOR PLANTS*

Tl_2SO_4 Amount in air-dry soil	First run harvested Oct. 29, 1932		Second run harvested Jan. 22, 1933		Third run harvested May 6, 1933		Fourth run harvested Nov. 18, 1933		Fifth run harvested Jan. 14, 1934		Sixth run harvested Mar. 10, 1934	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
p.p.m.	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
15	28	9.6	31	7.5	35	8.8	25	6.6	29	5.2	35	8.1
30	28	8.6	28	6.1	35	8.7	26	6.6	30	5.8	34	9.6
60	25	5.1	20	3.3	31	5.6	25	6.9	30	4.6	35	9.2
120	20	1.8	13	1.8	23	2.9	23	2.8	22	3.2	24	3.8
180	15	1.0	8	1.0	18	1.7	18	1.8	16	2.2	17	2.0
240	10	0.5	6	0.4	10	0.6	15	1.1	12	1.5	11	1.3
300	7	0.4	5	0.3	8	0.5	11	0.8	12	1.2	7	0.5
375	4	0.2	4	0.3	7	0.4	8	0.6	11	0.9	6	0.3
450	3	0.1	3	0.2	5	0.2	7	0.5	10	0.6	6	0.1
600	3	0.1	3	0.2	3	0.2	8	0.4	8	0.5	6	0.1
Check	28	9.4	28	8.0	33	8.3	24	6.2	30	5.3	32	8.6

Tl_2SO_4 amount in air-dry soil	Seventh run† harvested July 23, 1934		Eighth run harvested Oct. 27, 1934		Ninth run harvested Mar. 1, 1935		Tenth run harvested Nov. 20, 1935		Eleventh run harvested Feb. 3, 1936		Twelfth run harvested April 17, 1936	
	Ht.	*Wt.*	*Ht.*	*Wt.*	*Ht.*	*Wt.*	*Ht.*	*Wt.*	*Ht.*	*Wt.*	*Ht.*	*Wt.*
p.p.m.	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
15	12	3.7	28	4.2	28	5.2	23	5.6	29	6.8	31	9.2
30	12	3.6	25	3.3	29	5.5	22	5.3	28	5.9	32	8.1
60	12	4.0	28	4.4	28	5.6	24	5.9	29	5.8	29	8.4
120	12	3.6	26	3.4	24	3.3	22	3.5	24	3.3	33	7.6
180	9	2.1	19	1.6	16	1.5	16	1.6	18	1.4	24	3.2
240	7	1.1	14	1.0	11	0.8	10	1.0	14	0.8	17	1.6
300	5	0.5	9	0.5	8	0.6	9	0.4	12	0.4	10	0.6
375	4	0.4	7	0.3	7	0.5	8	0.3	14	0.3	8	0.2
450	4	0.2	7	0.2	6	0.4	8	0.2	8	0.2	7	0.1
600	4	0.1	6	0.2	6	0.3	7	0.2	9	0.2	7	0.1
Check	12	3.4	27	4.2	26	4.8	23	5.9	29	6.6	32	9.8

* All cultures run in triplicate; checks replicated six times. All values are averages of the replicates.

† Run No. 7 was conducted out of doors at Berkeley; all others were conducted in the greenhouse at Davis.

peated cropping upon the availability of this chemical. The results of the first, third, and fifth crops in comparison with crops with other sterilants have been reported (*3*). Table 1 gives the complete data on this experiment in terms of plant growth, which, of course, varies inversely

with toxicity. In this table rapid changes in toxicity are indicated by sudden changes in fresh weight, as between 60 p.p.m. and 120 p.p.m. in the first run.

The differences in toxicity evident in these results indicate a drop to about one-half the initial toxicity shown by the first run; then values tend to fluctuate in response to changes in light, temperature, and humidity; they follow no definite trend. Low values are shown in run 7,

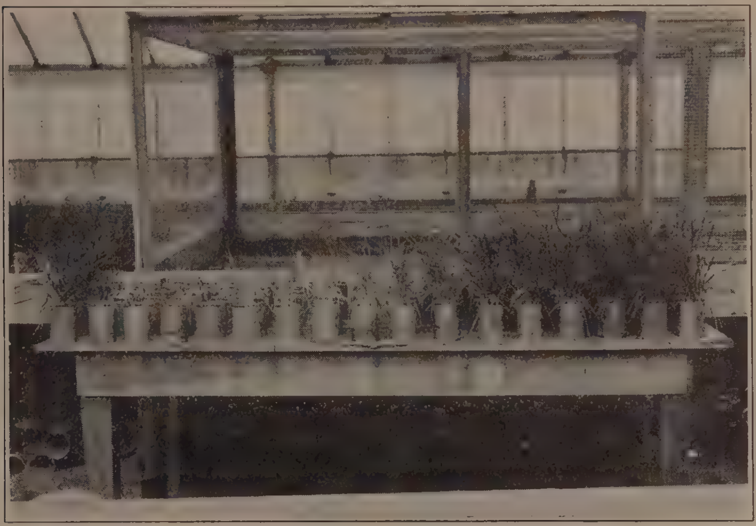

Fig. 1.—A concentration series with thallium sulfate in Yolo clay loam on test in the greenhouse. One row of checks is located at each end of the series. The concentration increases from right to left. Photograph taken on January 19, 1933, showing the first run reported in table 2.

probably because that run was conducted out of doors in Berkeley under conditions of high light intensity and high humidity. The other eleven runs were made in the greenhouse at Davis under conditions of low humidity during a large portion of the year.

The second toxicity experiment was conducted with four California soils, using thallium sulfate alone. The air-dry soils were moistened with solutions containing thallium sulfate in the concentrations given in the first column of table 2. Each culture was replicated five times, and the complete set run twice. Figure 1 shows the first run in the Yolo clay loam. Table 2 gives the yield data.

The differences in toxicity of thallium sulfate in the four soils is striking. They do not correlate well with water-holding capacities nor with the concentrations based on air-dry weights. No significant changes were

TABLE 2

Toxicity of Thallium Sulfate in Four Types of California Soils, as Shown by Growth of Indicator Plants

Tl_2SO_4 in moistening solution, p.p.m.	Yolo clay loam			Fresno sandy loam			Stockton adobe clay			Columbia fine sandy loam		
	Tl_2SO_4 in air-dry soil	Ht.	Wt.	Tl_2SO_4 in air-dry soil	Ht.	Wt.	Tl_2SO_4 in air-dry soil	Ht.	Wt.	Tl_2SO_4 in air-dry soil	Ht.	Wt.
First run, harvested January 29, 1933												
	p.p.m.	*cm*	*gm*	*p.p.m.*	*cm*	*gm*	*p.p.m.*	*cm*	*gm*	*p.p.m.*	*cm*	*gm*
25	7.5	32.5	10.6	3.3	20.6	3.4	5.8	12.7	1.5	3.7	21.2	5.4
50	15.0	30.7	10.0	6.5	20.1	3.3	11.7	12.7	1.4	7.5	22.4	5.7
75	22.5	29.5	9.4	9.8	19.6	3.0	17.5	12.5	1.3	11.2	21.4	5.4
100	30.0	28.4	9.1	13.1	18.3	3.0	23.3	9.5	1.0	15.0	21.2	5.6
150	45.0	27.0	7.8	19.6	18.1	3.0	35.0	9.7	1.1	22.5	20.3	5.1
200	60.0	24.0	5.1	26.2	16.5	2.6	46.6	9.0	1.0	30.0	20.1	5.2
275	82.5	21.2	3.4	36.0	14.0	2.0	64.2	7.5	0.5	41.2	20.5	4.6
350	105.0	18.8	2.5	45.8	12.8	1.6	81.7	7.7	0.6	52.5	19.0	4.3
450	135.0	13.7	1.5	58.9	12.0	1.5	105.0	5.3	0.5	67.5	18.3	4.3
550	165.0	11.9	1.8	72.0	9.2	1.0	128.5	5.1	0.4	82.5	16.3	3.1
650	195.0	12.5	1.3	85.0	7.9	0.9	151.8	5.0	0.4	97.5	15.2	2.6
800	240.0	4.8	0.5	104.6	5.1	0.7	186.8	4.8	0.3	120.0	12.5	1.9
1,000	300 0	6.0	0.9	131.0	3.8	0.3	233.3	4.4	0.3	150.0	10.4	1.7
1,500	450.0	5.0	0.5	196.1	3.0	0.2	350.0	3.9	0.3	225.0	6.5	1.1
2,000	600.0	5.0	0.6	262.0	2.5	0.2	467.0	3.5	0.3	300.0	5.8	0.9
Check	.....	31.5	10.0	.....	19.1	3.4	.....	12.5	2.0	.....	21.4	5.7
Check	.....	28.2	10.4	.....	20.5	3.8	.....	12.5	2.1	.....	21.5	6.2
Second run, harvested April 17, 1933												
	p.p.m.	*cm*	*gm*	*p.p.m.*	*cm*	*gm*	*p.p.m.*	*cm*	*gm*	*p.p.m.*	*cm*	*gm*
25	7.5	30.5	8.8	3.3	18.3	3.2	5.8	15.1	2.6	3.7	25.4	3.4
50	15.0	31.3	8.6	6.5	17.8	2.9	11.7	17.0	2.7	7.5	25.4	3.5
75	22.5	31.0	9.0	9.8	17.3	2.5	17.5	17.2	2.6	11.2	25.0	3.8
100	30.0	31 5	8.7	13.1	14.0	1.9	23.3	16.6	2.4	15.0	24.4	3.5
150	45 0	28.3	7.7	19.6	12.2	1.3	35.0	15.4	2.0	22.5	23.6	3.2
200	60 0	16 2	6.7	26.2	10.2	0.7	46.6	13.7	1.8	30.0	23.6	3.2
275	82.5	13 2	4.6	36.0	9.9	0.5	64.2	10.1	1.3	41.2	22.1	3.0
350	105 0	20.0	3.2	45.8	5.1	0.1	81.7	9.4	0.5	52.5	20.1	2.5
450	135 0	15.7	1.8	58.9	4.0	0.1	105.0	8.7	0.3	67.5	18.0	2.0
550	165.0	12.0	0.7	72.0	3.7	0.1	128.5	7.6	0.2	82.5	14.7	1.6
650	195 0	10.3	0.6	85.0	3.0	0.1	151.8	7.1	0.1	97.5	11.5	1.1
800	240 0	9.0	0.2	104.6	2.5	0.1	186.8	6.4	0.1	120.0	9.1	0.9
1,000	300.0	6.2	0.2	131.0	2.5	0.1	233.3	5.5	0.1	150.0	6.4	0.3
1,500	450 0	4.4	0.2	196.1	2.0	0.1	350.0	5.0	0.1	225.0	5.1	0.2
2,000	600 0	3 9	0.1	262.0	2.0	0.1	467.0	5.0	0.1	300.0	5.1	0.2
Check	.....	28 0	8.0	.....	17.8	3.2	.....	14.8	2.5	.....	26.0	3.8
Check	.....	30.5	9.0	.....	17.6	3.0	.....	14.8	2.5	.....	22.9	3.8

shown in the second run. This chemical shows extreme and persistent toxicity in soils of low fertility.

The response of the cereals to thallium sulfate in toxic concentrations is characteristic. Whereas chlorates and arsenic in toxic doses retard growth of the complete embryo, thallium checks the development of the shoot but has little effect on the coleoptile. Table 3 gives the relative development of shoots and coleoptiles of the oat seedlings 5 days after planting the second crop in two of the soils reported in table 2.

TABLE 3

RELATIVE DEVELOPMENT OF SHOOTS AND COLEOPTILES OF OATS GROWN IN THE SECOND RUN ON THALLIUM-TREATED SOILS, 5 DAYS AFTER PLANTING

Soil type	Plant part	Tl_2SO_4 in moistening solution, p.p.m.												Check
		100	150	200	275	350	450	550	650	800	1,000	1,500	2,000	
		cm	*cm*	*cm*	*cm*	*cm*	*cm*	*cm*	*cm*	*cm*	*cm*	*cm*	*cm*	*cm*
Yolo clay loam	Shoots	15.0	15.0	15.0	15.0	15.0	12.5	12.5	10.0	7.5	4.0	3.2	2.5	15.0
	Coleoptiles	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	4.5	4.0	4.0	4.0	5.0
Fresno sandy loam	Shoots	15.0	12.5	11.5	10.0	7.5	5.0	4.0	3.2	2.5	0.7	0.0	0.0	15.0
	Coleoptiles	5.0	5.0	5.0	5.0	5.0	5.0	4.4	4.0	4.0	3.8	3.2	2.5	5.0

In the higher concentrations the shoots grow very slowly, sometimes not protruding beyond the tips of the coleoptiles. In these extreme cases the seedlings usually die after two or three weeks. Where the chemical is less concentrated, the shoots continue growth; but with the development of the leaf blades they become chlorotic and weak. As shown in table 2, only the plants in the very low concentrations attained anything like normal development. Plants that make a perfectly normal start, as, for instance, those reported on the left in table 3, may subsequently show chlorosis, weakening, and decline. This fact is illustrated in table 2 where, in the second run in Fresno sandy loam, the plants in the culture containing 100 p.p.m. of Tl_2SO_4 in the soil solution made but little more than half the normal growth. These differences would be even greater if the plants were grown for a longer period.

Soil-Tube Tests.—The distribution of a sterilant within the soil after its application to the surface depends primarily upon the fixing power of the soil for the chemical. This property was studied by the soil-tube method previously described (*3*). Briefly, this consisted in slowly moistening columns of air-dry soil with Tl_2SO_4 solutions, dividing the columns each into 9 fractions of equal weight and approximately 10 cm in height, and growing oats upon the fractions. Results are shown in table 4.

TABLE 4

Fixing Power of California Soils for Thallium Sulfate as Shown by Growth of Indicator Plants in Fractions of the Treated Soil Columns*

Soil type	Fraction of column	H_2O check		Concentration of thallium sulfate in the moistening solution									
				25 p.p.m.		50 p.p.m.		100 p.p.m.		200 p.p.m.		400 p.p.m.	
		Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
	cm	cm	gm	cm	gm	cm	gm	cm	gm	cm	gm	cm	gm
Yolo clay loam harvested Jan. 24, 1933	0–10	19	3.2	17	2.0	13	1.1	13	0.7	10	0.6	4	0.4
	10–20	21	3.5	21	3.7	19	3.5	19	3.3	20	3.1	20	2.8
	20–30	20	3.7	19	3.0	20	3.5	19	3.2	20	3.4	19	3.6
	30–40	20	3.6	21	3.5	20	4.2	20	3.3	23	3.8	19	3.5
	40–50	21	3.6	20	3.3	20	3.8	19	3.5	20	3.2	19	4.2
	50–60	20	3.4	20	3.3	20	3.9	19	3.3	20	3.4	19	3.2
	60–70	22	3.9	21	3.3	30	9.2	21	4.2	27	7.0	28	8.0
	70–80	29	9.2	29	9.6	30	9.9	30	9.4	28	9.3	30	10.0
	80–90	27	7.5	27	6.5	31	10.0	31	7.9	29	7.6	23	6.3
Fresno sandy loam harvested Feb. 19, 1933	0–10	16	3.0	7	0.8	5	0.7	3	0.3	3	0.2	2	0.1
	10–20	17	2.9	15	2.5	15	2.8	15	2.9	15	2.9	12	2.6
	20–30	18	3.3	18	3.5	16	3.0	17	3.1	16	3.1	13	2.7
	30–40	18	3.0	18	3.2	18	3.2	17	3.4	17	3.0	15	3.1
	40–50	18	3.4	17	2.9	18	3.3	18	3.3	17	3.2	17	3.2
	50–60	17	3.2	18	3.2	18	3.6	16	3.0	17	3.1	19	4.0
	60–70	17	3.1	18	3.3	17	3.1	17	3.1	17	3.3	17	3.0
	70–80	17	3.2	17	3.2	17	3.2	17	3.2	17	3.2	17	3.1
	80–90	18	3.4	18	3.6	21	5.6	17	3.3	17	3.6	17	3.4
Stockton adobe clay harvested March 5, 1933	0–10	13	1.9	8	0.4	8	0.1	6	0.1	6	0.1	5	0.1
	10–20	14	2.0	13	2.1	13	2.0	15	2.2	14	1.9	14	1.7
	20–30	14	2.0	13	2.0	13	1.9	14	2.0	15	2.2	14	1.9
	30–40	14	2.1	13	2.0	13	2.0	14	2.1	14	2.1	14	1.9
	40–50	13	2.0	13	2.1	13	1.8	13	2.0	14	2.0	13	1.7
	50–60	14	2.2	13	1.9	14	2.2	14	2.2	14	2.0	14	1.6
	60–70	14	2.2	13	1.9	14	2.1	14	2.3	14	2.2	14	1.5
	70–80	14	2.3	14	2.3	14	2.3	14	2.2	13	2.0	13	2.1
	80–90	13	2.1	13	2.2	13	1.9	14	2.2	13	2.1	13	1.7
Columbia fine sandy loam harvested March 24, 1933	0–10	19	3.4	18	2.7	13	2.5	8	0.1	5	0.1	5	0.1
	10–20	20	3.3	20	3.3	19	3.6	20	3.0	20	3.1	18	3.2
	20–30	20	3.5	19	3.4	20	3.6	20	3.5	30	3.8	20	3.5
	30–40	21	3.7	20	3.6	20	4.0	20	3.6	20	3.8	20	3.6
	40–50	20	3.9	20	3.9	20	3.7	21	3.9	21	4.0	21	3.9
	50–60	20	3.7	20	3.8	21	3.9	20	4.0	20	3.8	20	3.8
	60–70	20	3.9	20	3.6	21	4.2	21	4.2	20	3.7	20	3.7
	70–80	23	5.8	21	5.8	23	4.7	25	6.6	23	4.6	25	7.2
	80–90	29	7.5	30	6.8	28	7.1	30	8.5	30	8.9	28	6.2

* Average fresh weight of plants in 12 untreated checks: Yolo clay loam, 9.9 grams; Fresno sandy loam, 3.3 grams; Stockton adobe clay, 2.0 grams; Columbia fine sandy loam, 5.3 grams.

Apparently all the chemical was held in the top 10 cm of soil in all these tests. In the more fertile soils, namely the Yolo clay loam and the Columbia fine sandy loam, there was appreciable leaching of soil nutrients. Since the moisture was so measured that it did not quite completely wet the soil, these nutrients were present in the lower portions of the soil columns and stimulated the plants in these fractions. In the Fresno sandy loam and Stockton adobe clay no appreciable leaching of nutrients

TABLE 5

FIXING POWER OF YOLO CLAY LOAM FOR THALLIUM SULFATE*
(Harvested April 10, 1933)

Fraction† of column	Concentration of Tl_2SO_4 in moistening solution, p.p.m.								Fraction‡ of column	Concentration of Tl_2SO_4 in moistening solution, p.p.m.	
	25		100		500		1,000			1,000	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.		Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*cm*	*gm*
0.0– 2.5	18	1.7	5	0.1	3	0.1	1	0.0	0.0– 1.2	1	0.0
2.5– 5.0	23	6.2	22	6.5	23	6.9	18	2.3	1.2– 2.5	1	0.0
5.0– 7.5	24	6.6	24	6.1	25	6.4	23	6.7	2.5– 3.7	8	0.2
7.5–10.0	25	7.2	25	6.9	25	6.3	25	7.0	3.7– 5.0	23	7.6
10.0–12.5	25	6.8	25	7.3	25	7.1	28	7.1	5.0– 6.2	25	7.8
12.5–15.0	25	6.8	26	7.3	28	7.5	26	6.7	6.2– 7.5	28	9.2
15.0–17.5	25	6.5	25	7.2	29	7.8	28	7.6	7.5– 8.7	28	8.5
17.5–20.0	25	6.9	26	7.3	28	7.6	26	6.9	8.7–10.0	28	9.1
20.0–22.5	25	7.1	28	7.4	28	7.0	26	6.9	10.0–11.2	28	9.3
22.5–25.0	26	7.3	28	7.6	28	7.1	27	7.2	11.2–12.5	27	8.7
25.0–27.5	28	7.6	28	8.1	27	7.2	26	7.1	12.5–15.0	27	8.2
27.5–30.0	25	6.7	28	7.4	27	7.0	27	6.8	15.0–17.5	27	9.0

* Average fresh weight of 10 untreated checks = 9.8 grams.

† Each fraction mixed with 375 grams air-dry soil and moistened with 112.5 cc tap water so that the culture has a thallium concentration one-quarter that of the moistening solution.

‡ Each fraction mixed with air-dry soil and tap water to make 650 grams of moistened soil per culture.

occurred; growth was uniform in all the lower fractions. The checks in column 3, table 4 were simply cultures in newly moistened soils.

Thallium sulfate is apparently held very firmly in all these soils. In none was there any evidence that the capacity of the soil for the sterilant was exceeded. The top 10 cm (table 4) held all the chemical applied to each tube. Since the quantity of moistening solution applied was just short of enough to wet the soil to the full depth, and this top fraction is one-ninth of the total depth, approximately one-ninth of the water would be held in this top fraction. Where the moistening solution contained 400 p.p.m., the concentration in the top fraction would therefore be 3,600 p.p.m. This was about 1,080 p.p.m. on the air-dry soil basis in the Yolo clay loam, 471 in the Fresno sandy loam, 840 in the Stockton adobe clay, and 540 in the Columbia fine sandy loam.

To ascertain the depth to which the chemical was penetrating, a series of 5 tubes was run using Yolo clay loam and fractionating into layers approximately 2.5 cm thick (table 5). These 2.5 cm portions were mixed in each case with 375 grams of air-dry soil. The mixtures were then placed in cans and moistened with 112.5 cc of tap water. In other words, the soil in each fraction was diluted with three parts of untreated soil. Consequently, in table 5 the concentrations of thallium sulfate expressed in terms of the moistening solution must be divided by 4 to give the actual values for the cultures. In the fifth tube the column was fractionated at each 1.2 cm, and the portions were made up to 650 grams of moistened soil by adding 7 parts of dry soil and wetting with tap water.

These results of what constitutes a more detailed study of the fixing of thallium sulfate by Yolo clay loam conclusively show that this chemical in solutions up to 500 p.p.m. in concentration will be all taken up in the top 2.5 cm of this soil from a volume sufficient to wet a 90-cm column (table 5). When the concentration reaches 1,000 p.p.m., the top 3.7 cm will hold the chemical. If the concentration in this top 3.7 cm were uniform, it would be 24,000 p.p.m. on the basis of the soil moisture or 7,200 p.p.m. in the air-dry soil. Since the growth was somewhat greater in the third culture, the concentration was probably greater in the top 2.5 cm. The capacity of Yolo clay loam to hold thallium sulfate may be safely estimated at around 10,000 p.p.m. on the dry-soil basis. In this soil, therefore, thallium is held up to a concentration of 1 per cent of its weight against the leaching effects of moving water in a form available to plants. Such a chemical, if applied to the soil, would remain in a relatively shallow layer for a considerable period, which renders it sterile to plant growth.

Most agricultural soils in California are subject to considerable moisture movement. The resistance of a chemical sterilant to the leaching effects of rains or irrigation is of vital importance. Thallium sulfate resists leaching to a marked degree, as shown by the following experiments. Tubes of air-dry soils, moistened with solutions containing 100 p.p.m. and 200 p.p.m. of thallium sulfate, were leached with varying amounts of distilled water. When the leaching was finished they were allowed to come to equilibrium by standing with their lowermost layers in contact with air-dry soil until the moisture stopped moving. They were then fractionated, planted with oats, and at the end of a 30-day period the oats were harvested as in the previous tests. Tables 6, 7, 8, and 9 present the data on these experiments.

With the Yolo clay loam, as the volume of water used in leaching becomes great enough to carry the soil nutrients out of the tube, the

TABLE 6

RESULTS OF LEACHING THALLIUM SULFATE IN YOLO CLAY LOAM WITH DIFFERENT DEPTHS OF WATER, AS SHOWN BY GROWTH OF INDICATOR PLANTS*

Tl_2SO_4, 100 p.p.m. in moistening solution, cultures harvested January 27, 1933

Depth	Leached with 5 cm H_2O		Leached with 10 cm H_2O		Leached with 15 cm H_2O		Leached with 20 cm H_2O		Leached with 25 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0–10	7	1.1	5	0.6	7	1.6	10	0.8	13	2.2
10–20	19	3.9	20	3.4	20	3.6	18	3.2	19	3.5
20–30	19	3.8	21	4.4	20	3.7	19	3.4	20	4.3
30–40	20	4.2	22	3.8	20	3.6	19	3.1	19	3.8
40–50	22	3.6	22	3.5	19	3.3	19	3.5	19	3.8
50–60	22	3.9	22	3.5	19	3.5	19	3.6	20	4.7
60–70	24	5.8	21	3.4	18	2.9	18	3.2	18	3.5
70–80	30	10.0	20	3.4	18	3.1	19	3.4	19	3.8
80–90	30	10.9	29	11.0	19	3.7	18	3.3	18	3.5

Tl_2SO_4, 200 p.p.m. in moistening solution, cultures harvested February 7, 1933

Depth	Leached with 37.5 cm H_2O		Leached with 50 cm H_2O		Leached with 75 cm H_2O		Leached with 125 cm H_2O		Leached with 200 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0–10	5	0.5	5	0.5	5	0.4	5	0.5	5	0.4
10–20	22	4.0	20	4.2	22	4.5	18	4.2	17	3.0
20–30	22	4.3	19	3.6	23	5.2	20	4.7	18	4.0
30–40	22	4.5	20	4.0	24	5.0	20	4.8	19	4.1
40–50	22	4.7	20	3.9	23	5.2	20	4.2	19	3.8
50–60	23	5.2	21	4.4	22	3.6	20	4.2	18	3.2
60–70	20	3.9	22	4.3	22	3.7	18	3.3	17	3.0
70–80	20	3.9	20	4.4	22	4.0	17	3.0	17	3.2
80–90	20	4.1	20	4.0	22	4.6	15	2.8	15	2.6

Check tubes moistened with water, cultures harvested February 7, 1933

Depth	Leached with 37.5 cm H_2O		Leached with 50 cm H_2O		Leached with 75 cm H_2O		Leached with 125 cm H_2O		Leached with 200 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0–10	19	4.0	18	3.4	19	3.8	18	3.5	17	3.0
10–20	19	3.8	19	3.7	20	4.3	18	3.7	17	3.1
20–30	20	4.1	20	4.0	20	4.2	18	3.5	17	3.2
30–40	19	3.7	23	4.9	20	4.6	19	4.1	18	4.0
40–50	19	4.0	21	4.2	19	4.0	17	3.1	19	3.4
50–60	20	4.3	22	4.5	20	4.4	17	3.2	20	4.7
60–70	19	4.3	19	3.6	19	3.3	17	3.1	19	3.7
70–80	19	3.7	19	3.4	20	4.0	18	3.3	21	4.5
80–90	19	4.3	19	3.5	19	3.9	19	3.5	19	3.6

* Average weight of plants in 30 untreated checks = 11.6 gm.

TABLE 7

RESULTS OF LEACHING THALLIUM SULFATE IN FRESNO SANDY LOAM WITH DIFFERENT DEPTHS OF WATER, AS SHOWN BY GROWTH OF INDICATOR PLANTS*

Tl_2SO_4, 100 p.p.m. in moistening solution, cultures harvested February 16, 1933

Depth	Leached with 5 cm H_2O		Leached with 10 cm H_2O		Leached with 15 cm H_2O		Leached with 20 cm H_2O		Leached with 25 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0–10	1	0.1	1	0.1	1	0.2	1	0.2	1	0.1
10–20	14	2.6	14	2.3	13	2.4	14	2.3	13	2.1
20–30	14	2.6	14	2.4	13	2.2	13	2.5	15	2.8
30–40	13	2.5	14	2.6	13	2.4	14	2.8	14	2.3
40–50	14	2.7	14	2.6	13	2.5	14	2.5	14	2.7
50–60	14	2.9	14	2.8	14	2.7	15	2.6	14	2.4
60–70	14	2.7	14	2.8	14	2.6	14	2.5	14	2.8
70–80	14	2.8	14	2.9	14	2.4	14	2.4	14	2.7
80–90	14	3.1	15	2.8	14	2.4	15	2.5	14	2.3

Tl_2SO_4, 200 p.p.m. in moistening solution, cultures harvested March 20, 1933

Depth	Leached with 37.5 cm H_2O		Leached with 50 cm H_2O		Leached with 75 cm H_2O		Leached with 125 cm H_2O		Leached with 200 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0–10	3	0.1	3	0.1	2	0.1	1	0.1	2	0.1
10–20	15	2.7	15	2.7	15	2.7	14	2.5	14	2.4
20–30	14	2.5	15	2.8	15	2.7	15	2.6	15	2.8
30–40	15	2.6	15	2.8	15	2.8	15	2.7	15	2.9
40–50	16	2.8	16	2.8	16	2.7	15	3.2	16	2.9
50–60	14	2.6	16	2.9	14	2.8	15	2.9	16	3.0
60–70	14	2.8	15	2.9	14	2.7	14	2.9	15	2.8
70–80	15	2.6	15	2.9	15	2.5	15	2.8	16	2.7
80–90	15	2.8	15	2.7	15	2.3	14	2.6	18	3.3

Check tubes moistened with water, cultures harvested March 20, 1933

Depth	Leached with 37.5 cm H_2O		Leached with 50 cm H_2O		Leached with 75 cm H_2O		Leached with 125 cm H_2O		Leached with 200 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0–10	15	2.7	16	2.5	15	2.7	13	2.4	14	2.2
10–20	16	2.9	16	2.7	15	2.7	15	2.7	15	2.5
20–30	15	2.9	17	3.0	15	2.8	15	2.9	15	2.7
30–40	15	2.9	18	3.1	17	2.9	15	2.9	16	3.0
40–50	16	2.9	17	2.8	18	3.1	16	2.8	18	3.0
50–60	15	2.9	18	3.1	17	3.0	17	2.9	18	3.1
60–70	16	2.9	16	2.7	16	3.1	18	2.8	20	3.6
70–80	15	2.8	18	3.0	18	3.0	17	2.7	19	2.8
80–90	16	3.0	18	3.0	17	2.8	18	3.1	17	2.7

* Average weight of plants in 30 untreated checks = 3.5 gm.

TABLE 8

RESULTS OF LEACHING THALLIUM SULFATE IN STOCKTON ADOBE CLAY WITH DIFFERENT DEPTHS OF WATER, AS SHOWN BY GROWTH OF INDICATOR PLANTS*

Tl_2SO_4, 100 p.p.m. in moistening solution, cultures harvested March 5, 1933

Depth	Leached with 5 cm H_2O		Leached with 10 cm H_2O		Leached with 15 cm H_2O		Leached with 20 cm H_2O		Leached with 25 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0–10	5	0.1	5	0.1	7	0.2	7	0.1	7	0.1
10–20	13	1.7	13	1.7	13	2.1	13	1.7	12	1.7
20–30	13	2.0	13	2.1	14	2.1	13	2.1	13	1.9
30–40	13	2.0	13	1.9	14	2.1	14	2.2	13	1.8
40–50	13	1.7	14	2.1	13	1.9	14	2.3	14	2.1
50–60	12	2.0	13	2.0	14	2.2	14	2.0	14	2.2
60–70	14	2.2	14	2.1	14	2.0	14	2.2	14	2.3
70–80	14	2.2	13	2.0	13	2.1	14	2.2	14	2.1
80–90	14	2.2	13	2.2	13	2.0	13	2.1	14	2.3

Tl_2SO_4, 200 p.p.m. in moistening solution, cultures harvested March 20, 1933

Depth	Leached with 37.5 cm H_2O		Leached with 50 cm H_2O		Leached with 75 cm H_2O		Leached with 125 cm H_2O		Leached with 200 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0–10	2	0 1	2	0.1	2	0.1	2	0.1	2	0.1
10–20	18	2 0	15	1.7	15	2.1	15	1.9	18	1.7
20–30	18	2.1	16	1.8	17	1.7	15	1.9	15	1.9
30–40	15	1 6	17	2.1	18	1.9	17	2.0	16	1.9
40–50	17	2 0	17	1.7	16	1.9	18	1.8	16	1.9
50–60	17	1 9	18	1.9	17	1.8	17	2.2	16	1.8
60–70	18	2.0	17	1.7	17	1.9	17	1.8	16	2.1
70–80	17	2 0	17	2.1	17	2.1	16	1.9	17	2.1
80–90	18	2.1	16	1.8	16	1.9	15	1.7	16	1.7

Check tubes moistened with water, cultures harvested March 20, 1933

Depth	Leached with 37.5 cm H_2O		Leached with 50 cm H_2O		Leached with 75 cm H_2O		Leached with 125 cm H_2O		Leached with 200 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0–10	15	1.7	15	1.7	15	1.6	15	1.9	15	2.0
10–20	15	1.6	15	1.7	15	1.7	15	2.0	15	1.9
20–30	15	1.8	15	1.8	15	1.9	15	1.8	15	1.9
30–40	15	1.8	15	1.8	15	1.9	15	2.1	15	1.9
40–50	15	1.8	15	1.8	16	1.9	15	1.7	16	2.1
50–60	15	2.0	15	1.9	16	1.9	15	1.8	15	2.2
60–70	15	1.9	15	1.8	15	1.8	15	1.9	15	1.9
70–80	15	1.9	15	1.8	15	1.8	15	1.9	16	2.1
80–90	16	1.9	15	1.9	15	1.8	15	1.8	15	1.9

* Average weight of plants in 30 untreated checks = 1.9 gm.

TABLE 9

RESULTS OF LEACHING THALLIUM SULFATE IN COLUMBIA FINE SANDY LOAM WITH DIFFERENT DEPTHS OF WATER, AS SHOWN BY GROWTH OF INDICATOR PLANTS*

Tl_2SO_4, 100 p.p.m. in moistening solution, cultures harvested March 23, 1933

Depth	Leached with 5 cm H_2O		Leached with 10 cm H_2O		Leached with 15 cm H_2O		Leached with 20 cm H_2O		Leached with 25 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0–10	5	0.1	7	0.2	10	0.3	18	0.8	18	1.5
10–20	20	3.3	21	3.2	21	3.4	23	3.2	22	3.0
20–30	19	3.2	20	3.1	23	3.4	20	2.8	22	3.4
30–40	19	3.1	23	3.6	22	3.4	22	3.1	23	3.3
40–50	18	3.0	21	3.2	20	2.9	20	3.1	23	2.9
50–60	20	3.8	20	3.3	20	3.0	20	2.9	22	3.1
60–70	23	3.7	19	3.4	19	2.8	20	2.7	21	2.8
70–80	23	3.8	23	3.8	21	3.5	20	2.8	23	3.2
80–90	21	4.3	21	3.7	23	3.9	20	2.8	21	2.7

Tl_2SO_4, 200 p.p.m. in moistening solution, cultures harvested April 4, 1933

Depth	Leached with 37.5 cm H_2O		Leached with 50 cm H_2O		Leached with 75 cm H_2O		Leached with 125 cm H_2O		Leached with 200 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0–10	10	0.3	10	0.7	7	0.6	6	0.5	6	0.3
10–20	15	2.3	18	2.3	18	2.4	18	2.2	18	2.3
20–30	16	2.5	18	2.4	18	2.7	18	2.2	18	2.7
30–40	18	2.2	18	2.5	19	2.3	18	2.8	18	2.3
40–50	18	2.5	20	2.7	18	2.6	18	2.2	17	2.3
50–60	19	2.4	18	2.5	18	2.7	18	2.4	15	2.7
60–70	19	2.4	18	2.5	19	2.8	18	2.6	18	2.9
70–80	18	2.5	18	2.7	18	2.5	19	2.6	18	2.7
80–90	18	2.4	20	2.6	20	2.7	18	2.7	17	2.4

Check tubes moistened with water, cultures harvested April 4, 1933

Depth	Leached with 37.5 cm H_2O		Leached with 50 cm H_2O		Leached with 75 cm H_2O		Leached with 125 cm H_2O		Leached with 200 cm H_2O	
	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
cm	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
0–10	18	2.3	17	2.1	18	2.3	18	2.4	15	2.2
10–20	19	2.4	18	2.2	18	2.2	17	2.2	15	2.0
20–30	18	2.3	18	2.3	18	2 4	18	2.3	16	2.6
30–40	18	2.5	18	2.3	19	2.3	18	2.3	18	2.5
40–50	18	2.7	18	2.3	18	2.3	18	2.6	16	2.1
50–60	18	2.4	19	2.5	18	2.4	19	2.5	18	2.5
60–70	18	2.2	19	2.4	19	2.3	18	2.2	18	2.5
70–80	18	2.3	18	2.3	19	2.2	20	2.6	18	2.4
80–90	18	2.3	19	2.5	20	2.5	19	2.4	18	2.6

* Average weight of plants in 10 untreated checks = 5.5 grams for March 23, 1933, cultures; average of those in 30 untreated checks = 3.1 grams for April 4, 1933, cultures.

stimulated growth found in the lower fractions, with little or no leaching, does not occur. Likewise with the greater amounts of water, there is some indication that when the moistening solution contains only 100 p.p.m. of Tl_2SO_4 the toxicity in the top 10 cm becomes somewhat lessened. When the moistening solution carries 200 p.p.m. of Tl_2SO_4, up to 200 cm of water has no effect upon the toxicity in this top fraction. There is no significant reduction in growth in any of the lower fractions. If leached, the chemical is carried downward in a subtoxic concentration.

With Fresno sandy loam the results are very much the same. Leaching with volumes equivalent to as much as 200 cm of water has no discernible effect upon the location or toxicity of the thallium sulfate within the limits of this experiment. Especially in the less fertile soils, this toxicant is evidently firmly fixed and resists leaching strongly. There is a slight indication that in the Yolo and Columbia soils, where the toxic concentration is higher, when moistening was done with solutions containing 100 p.p.m. of Tl_2SO_4 there was some movement of chemical, and growth was increased. This evidence, however, is hardly conclusive.

Toxicity of Bait.—The next experiments were designed to show the effect of thallium-treated grain upon the growth of adjacent plants. Two types of bait were used: potted barley, which had received the normal treatment[5] with thallium sulfate in preparation for field use, and whole barley similarly treated. Kanota oats were used as the indicator plants. Cans containing 500 grams each of dry Yolo clay loam were moistened and planted with the oats. Then the kernels of treated grain were placed in the soil in the same manner as the oats, the distances between the oats and the poisoned grain being varied. Table 10 summarizes the data on these tests, including checks grown at the same time. The whole treated barley germinated and some of the plants grew (table 10). Since the potted barley was heated in the hulling process, the embryos were killed and the kernels did not germinate when planted.

There were planted 470 treated barley seeds in all these tests, of which 246 grew, a survival of practically 50 per cent. These 246 plants weighed 129.9 grams, the average fresh weight per plant being 0.53 gram, 47 per cent of that of the untreated check barley.

In the experiments on the effects of the thallium-treated grain on oat plants, the variation in number of plants per can renders the average weight per plant of little value; but the average total fresh weight per can of oats grown is a fair basis for comparison. These data show that with the 0.25-cm spacing the growth is about 30 per cent less than that of the check plants of untreated oats; with the wider spacing no significant

[5] This treated grain carried 1 per cent Tl_2SO_4 by weight.

differences can be detected. Evidently the sterilizing effect of thallium-coated grain broadcast on the land as bait will be strictly localized and, if the bait is properly scattered, little or no reduction in the natural growth of plants should occur, even if the grain remained on the land through the winter following the application.

TABLE 10

EFFECTS OF THALLIUM-TREATED GRAIN UPON ADJACENT PLANTS IN YOLO CLAY LOAM

Spacing of plants	Description of plants	Total number of plants	Average number of plants per can	Total fresh weight	Average fresh weight per can	Average fresh weight per plant
	Whole barley tests					
cm				*gm*	*gm*	*gm*
	Treated whole barley	38	7.6	16.4	3.28	0.43
0.25	Oats, indicator plants	37	7.4	23.5	4.70	0.63
	Barley and oats—5 cans	75	15.0	39.9	7.98	0.53
	Treated whole barley	59	11.8	18.7	3.74	0.32
0.50	Oats, indicator plants	56	11.2	39.9	7.98	0.71
	Barley and oats—5 cans	115	23.0	58.6	11.72	0.51
	Treated whole barley	35	7.0	14.0	2.80	0.40
1.00	Oats, indicator plants	59	11.8	45.6	9.12	0.77
	Barley and oats—5 cans	94	18.8	59.6	11.92	0.63
	Treated whole barley	33	3.3	16.8	1.68	0.51
2.00	Oats, indicator plants	77	7.7	91.8	9.18	1.19
	Barley and oats—10 cans	110	11.0	108.6	10.86	0.99
	Potted barley tests*					
cm				*gm*	*gm*	*gm*
0.25	Oats, total 5 cans	50	10.0	41.9	8.38	0.84
0.50	Oats, total 5 cans	58	11.6	46.0	9.20	0.79
1.00	Oats, total 5 cans	79	15.8	56.2	11.24	0.71
2.00	Oats, total 10 cans	76	7.6	94.9	9.49	1.25
	Check plants					
				gm	*gm*	*gm*
	Treated whole barley	81	8.1	64.0	6.40	0.79
	Untreated whole barley	100	10.0	113 2	11.32	1.13
	Untreated oats	100	10.0	117.6	11.76	1.18

* Growth of indicator oats. Potted barley, being heated in the hulling process, does not germinate.

Another series of tests was made in the greenhouse to find the effect of thallium-coated grain upon growing oats, the bait being applied 10 days after the oats were planted. Twenty cans of Yolo clay loam were moistened and planted on February 7, 1933. The seeds germinated on February 11, and the seedlings were growing rapidly by February 12. On February 17 eight cans received thallium-coated grain (potted-barley

bait) in varying dosages, eight cans received equivalent dosages of thallium sulfate, applied in solution, and four cans remained as checks. The data on these series are given in table 11. The cultures were watered every 2 or 3 days, and the chlorosis characteristic of thallium injury soon appeared. The plants that received the larger doses of thallium sulfate continued to show injury in the cultures, but those receiving less of the chemical showed some signs of recovery toward the end of the test. Judging from these figures, very large dosages of poisoned barley would be required to affect the existing growth of plants in the field. There was a significant difference between the effects of the thallium from the two different methods of application. Apparently the chemical is absorbed by the potted barley and held so that it will not wash off. In these tests the bait lay on top of the soil and was flooded with each irrigation. Probably the chemical that did wash off was quickly fixed in the soil, above the zone of active roots.

TABLE 11

EFFECT OF THALLIUM SULFATE FROM BAIT AND IN SOLUTION ON GROWING PLANTS

Tl_2SO_4*			Bait treatment				Solution treatment, growth of plants†	
			Potted barley*		Growth of plants†			
Per culture	Per acre	P.p.m. of air-dry soil	Per culture	Per acre	Height	Weight	Height	Weight
gm	*lbs.*	*p.p.m.*	*gm*	*lbs.*	*cm*	*gm*	*cm*	*gm*
0.0	0.0	0.0	0.0	0	25	10.7	24	10.0
0.0	0.0	0.0	0.0	0	25	10.9	25	10.4
0.005	8.3	10.0	0.5	830	25	11.0	25	11.3
0.010	16.6	20.0	1.0	1,660	25	10.7	25	11.2
0.025	41.5	50.0	2.5	4,150	25	10.9	24	11.0
0.050	83.0	100.0	5.0	8,300	25	10.0	25	9.2
0.100	166.0	200.0	10.0	16,600	23	8.7	23	4.9
0.150	249.0	300.0	15.0	24,900	23	9.1	20	4.5
0.200	332.0	400.0	20.0	33,200	23	7.9	20	4.6
0.300	498.0	600.0	30.0	49,800	21	5.9	15	1.4

* In the bait treatment, the thallium sulfate was applied by means of thallium-coated grain; the amount of grain applied to give the dosage is reported in the fourth column.

† Plants per can=10.

Field-Plot Tests.—One further experiment was made with thallium-coated grain on square-foot plots in the field. In an enclosure in the corner of a pasture two areas covering approximately 49 square feet each were laid out. After the plots had been treated, the whole was covered with a cage of ¼-inch mesh galvanized hardware cloth. The treatments were made on February 10, 1933, and the areas were harvested on May 4. Table 12 gives the dosages and weights of harvested plants on these plots.

Two sets of plots were laid out, each on a checkerboard pattern, and all intervening areas were harvested as checks.

The only plots in this test showing significant reductions in yield are Nos. 23 and 48. These received 28.35 grams or 1 ounce each of poisoned grain, scattered evenly over the square-foot area. The cover of grass and range plants was noticeably thinner on these areas. The grain on plots 25 and 50 was piled in the center of each plot; but the area actually covered was so small that, although bare of vegetation, it had little effect on the yield of the total plot. No. 25 is somewhat reduced in comparison with Nos. 20 and 24, the two adjacent check plots. No. 50 shows no significant reduction. After these plots were laid out, 2.91 inches of rain fell; and the thallium chlorosis could be observed on the plants of the more heavily treated plots while they were young. As the season advanced they seemed to recover; and at harvest time little permanent injury was found, except as noted above. The following year, when these plots were harvested again no significant differences in yield were found on any of them.

TABLE 12

The Effect of Thallium-Sulfate-Treated Grain upon Growing Pasture Plants

Plot No.	Dosage per sq. ft.	Fresh weight of crop	Plot No.	Dosage per sq. ft.	Fresh weight of crop
	gm	*gm*		*gm*	*gm*
1	0.22	153.35	26	0.22	76.30
2	check	102.35	27	check	78.00
3	0.44	129.30	28	0.44	105.20
4	check	121.80	29	check	135.15
5	0.89	137.70	30	0.89	105.00
6	check	163.10	31	check	101.35
7	check	121.80	32	check	103.25
8	check	151.60	33	check	115.45
9	check	111.80	34	check	114.85
10	check	115.10	35	check	167.75
11	1.77	130.35	36	1.77	124.85
12	check	85.15	37	check	96.00
13	3.54	125.00	38	3.54	159.80
14	check	123.55	39	check	127.35
15	7.09	111.65	40	7.09	150.75
16	check	120.45	41	check	137.60
17	check	129.65	42	check	130.90
18	check	154.30	43	check	158.65
19	check	163.10	44	check	115.65
20	check	147.15	45	check	136.70
21	14.17	104.85	46	14.17	114.90
22	check	106.10	47	check	95.75
23	28.35	85.30	48	28.35	87.60
24	check	155.10	49	check	164.55
25	56.70	112.45	50	56.70	145.10

DISCUSSION

The physiological effect of thallium upon plants has not been studied extensively. The differential effect upon the growth rate of shoot and coleoptile of oats is shown in table 3. Since the shoot is formed by cell division in the embryo, whereas the coleoptile develops mainly by enlargement of previously formed cells, meristematic regions may respond characteristically to this element. Chlorosis of older tissues seems to be a constant symptom of thallium poisoning but may be entirely secondary.

Some excellent work has been done at Charles University in Prague by Prat and his colleagues (*5*) on the absorption of thallium salts from water and from nutrient solutions by plants. Using broad beans and corn, these workers found that practically all the chemical was absorbed within 72 hours from a $TlNO_3$ solution 1×10^{-4} molecular in concentration. The plants died in 2 to 4 days. The same amount of thallium nitrate in a nutrient solution (Shive R_5C_2) had little effect on the plants. Although they absorbed the nutrient salts, the thallium remained in the solution unchanged in amount for 5 to 10 days, and only 10 per cent to 40 per cent was absorbed in 13 days. Whereas plants readily absorb thallium from pure water solution, but little was taken up from nutrient solutions or from balanced solutions containing $CaCl_2$.

These workers (*5*) also found a definite effect of thallium upon meristematic cells. These cells take on a mature appearance, and division becomes abnormal and ceases after 48 hours. The illustrations given by them show a pronounced stunting of the roots of plants affected by thallium; large necrotic areas appear on the primary root, and many secondary roots are killed. These effects are much less evident on the plants from the nutrient solutions. Apparently little thallium should be absorbed from soils, especially from those favorable for plant growth.

The writer ashed the tops of several plants that were chlorotic from the presence of thallium in the soil. The ash, moistened with a few drops of concentrated HCl, was heated to dryness and extracted with $\frac{N}{10}$ HCl. A sample of the supernatant liquid was sent to Heyrovsky for analysis by means of the Polarograph. Heyrovsky[6] replied concerning the sample: "I could not ascertain any thallium in it." This statement checks with the results of the workers at Prague. Apparently the chlorosis may be a secondary response to the effect of thallium upon the roots. If this element is present in the tops of affected plants, it occurs in such minute amounts that the sensitive Polarograph method cannot detect it. The

[6] Personal correspondence from Professor J. Heyrovsky, June 5, 1933.

roots of these plants were small and unhealthy. Often the plants could be pulled out of the soil, most of the roots breaking off or the xylem pulling out, leaving the cortical tissue behind.

Evidently thallium is very toxic to plants that are growing in water or in poorly balanced solutions. As table 2 indicates, the toxicity of this element varies in different soils, being less toxic in those which are most fertile. Probably lack of fertility reflects a condition in the soil solution that favors absorption of the poison much as does distilled water. Whether this condition is caused by a deficiency in certain mineral nutrients is hard to say without further study; but the assumption seems reasonably well justified, at least in the soils under consideration.

The workers at Prague (*5*) found appreciable injury to roots of plants in a nutrient solution (Shive R_5C_2 conc. 0.88 Atm.) containing 1×10^{-4} molecular $TlNO_3$. In distilled water containing a like amount of thallium, the plants soon died. This concentration of $TlNO_3$ corresponds to about 27 p.p.m. in the solution.

In Yolo clay loam (table 2) about 50 per cent growth took place at 60 p.p.m. in the soil, and complete sterility occurred at 240 p.p.m. The corresponding concentrations in the less fertile soil are roughly 46 p.p.m. and 131 p.p.m. The concentrations in the soil solution at field capacity would be three times as great in Yolo clay loam and up to six times as great in lighter soils. Apparently the fixation of thallium compounds in soils renders them less available to plants than they are in solutions. This factor, in addition to the antagonistic action in the balanced solution, makes the critical concentrations in soils fairly high. For complete sterility, apparently, the thallium concentration in the soil must reach 100 p.p.m. or more on a basis of Tl_2SO_4. For fertile soils it would be even somewhat higher.

McCool (*4*) found much higher toxicities in his experiments. Though his method of mixing the chemical in the soil is questionable, probably the more important factors causing these differences were the soils and plant species used. Soils from the humid eastern United States probably compare more nearly with the Fresno and Stockton soils in fertility than with the recent alluvial Yolo and Columbia series. Toxicities would undoubtedly run high in the former soils. On the average, furthermore, the cultivated varieties of plants used by McCool were probably more susceptible than the oats used in the experiments here reported. Most range plants in California would probably be even more tolerant of thallium sulfate in the soil.

Two vital factors are involved in the problem of soil sterility as related to the control of rodents by thallium-treated grain. The first is the

quantity of thallium being placed on the soil per unit area; the second is the final disposition of this poison. To render a soil sterile against annual weeds, one must provide a minimum toxic concentration of the chemical in at least the top inch. An acre-inch of soil weighs roughly 300,000 pounds, and 30 pounds of Tl_2SO_4 would be required to render it sterile. For a 50 per cent reduction in growth, 15 pounds would be needed. Perennial plants would be little affected by even larger doses than this. Considering the fixing power of soils for thallium compounds, even greater amounts of the chemical would be necessary for complete sterilization.

From the high saturation capacity indicated by the data in table 5, an acre-inch of soil could hold up to one hundred times the amount of thallium sulfate required to render it sterile. This fact is important in relation to the distribution of the chemical in rodent control. The usual practice in distributing the bait is to spread one spoonful[7] containing about 20 grams of poisoned grain over an area of 3 to 6 square feet. A bait contains approximately 400 kernels. If each of these was able to sterilize 1 square centimeter (table 10), then seven to fourteen applications would be required to cover the original 3 to 6 square feet, and over 100,000 baits to cover an acre. This would be equivalent to roughly 5,000 pounds of grain bearing 50 pounds of Tl_2SO_4, and a lethal concentration of the chemical would be provided in the top 1.2 cm of soil if evenly distributed. The actual depth of penetration would probably be much less than this, and many seeds should be able to germinate and grow from below this level. Table 10 also shows that there would be no effect during the first year.

These calculations have been based on the sterilizing capacity of baits lying on the surface of the soil. If the baits were eaten by rodents, the chemical would be distributed, by death of the squirrels, more or less at random, through the top several feet of soil; and immensely greater amounts of thallium would obviously be required to have any appreciable effect. Only animals dying on the surface would leave the thallium in a position to affect the top soil. Such an occasion is rare.

When the problem is viewed from the standpoint of field practice, the disparity between the figures given above and the actual amounts used in rodent control is striking. In an initial campaign with thallium-treated bait, average dosage may run up to a pound of grain per acre or more. Because of the effectiveness of this poison, however, the dosage may be rapidly reduced. In one California county the average dosage had decreased to $\frac{1}{35}$ of a pound of bait per acre in five years. Since this

[7] A standardized spoon of definite size is used for this purpose.

bait carried only 1 per cent Tl_2SO_4 by weight, evidently the chemical reaching the soil is negligible as compared with that required for sterilization.

Though the results of these studies are of little value in the actual field of soil sterilization and are mostly negative in relation to the rodent-control problem, one point seems noteworthy. If sterilization of soil by thallium-treated grain should ever occur, it would result from the accumulation of untaken baits. This grain would also be a source of danger to other animals and would represent a waste of material. This poison, therefore, should be handled by competent and experienced men so that the majority of baits will be placed where they will be taken. If this precaution is observed, soil sterilization is not a factor in the control of ground squirrels with thallium-treated grain.

It is regrettable that such warnings as those of Brooks (*1*, p. 106) and McCool (*4*, p. 295) should be issued without some preliminary study of the actual field practice involved.

SUMMARY

Experiments indicate that thallium sulfate is very toxic in soils. Thirty pounds will sterilize an acre-inch of average soil. Toxicity decreases, however, with time and cropping.

Thallium toxicity varies with soil type, a range of three times or more having been shown in the soils studied.

The toxicity of thallium is greater in soils low in fertility. It cannot be correlated with the soil type nor with water-holding capacity.

Thallium toxicity is evidenced by retarded shoot growth, a nearly normal development of the coleoptile, chlorosis of leaves, stunting of older plants, and early death where the concentrations are high.

Thallium sulfate was strongly fixed in four soils. The saturation capacity of Yolo clay loam for this chemical was about 10,000 p.p.m. on a dry-weight basis.

Leaching with as much as 200 cm of distilled water had practically no effect upon the thallium toxicity in these soils.

Thallium-treated barley, as commonly used for squirrel bait, had little or no effect upon germination or growth of oats planted in the same can and spaced within 0.5 cm of the grains. Growth was reduced when the spacing was 0.25 cm. Thallium-treated whole barley gave a 50 per cent germination, and the fresh weight of the seedlings at 30 days was 47 per cent of that of the checks.

Oat seedlings were unaffected by the application of treated barley to the soil, followed by irrigation, except where the dose was excessive.

Thallium-treated barley also had little effect upon growing plants in a pasture area. The heaviest application, equivalent to over 2,500 pounds of grain to the acre, reduced the growth less than 50 per cent.

Workers at Charles University, Prague (*5*), have shown that plants do not readily absorb thallium salts from balanced nutrient solutions. Ashed plants from the test here reported failed to give a thallium test by the sensitive Polarograph method of Heyrovsky.

Thallium sulfate in concentrations of 100 p.p.m. or more on a dry-weight basis should be completely toxic in most soils. The concentration at saturation would be around a hundred times this value.

About 30 pounds of thallium sulfate uniformly distributed would be required to sterilize an acre-inch of soil. Under natural conditions of application it would probably be tied up in a much shallower layer of soil. At least 5,000 pounds of squirrel bait, carrying 1 per cent Tl_2SO_4 uniformly distributed, would be necessary to sterilize an acre completely.

If the baits are taken by squirrels, the thallium is distributed at random in localized regions in the top several feet of soil. Under these conditions the dosage mentioned above would give no sterilization except where an animal might die on the surface.

In actual field practice, dosage seldom exceeds 1 pound of thallium-treated grain per acre, bearing 0.01 pound of Tl_2SO_4. Dosage rapidly decreases as the rodents are brought under control.

The differences between these rates of dosage and those mentioned above show that little need be feared from the sterilization of soils by thallium-treated squirrel bait.

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TOXICITY OF ARSENIC, BORAX, CHLORATE, AND THEIR COMBINATIONS IN THREE CALIFORNIA SOILS

A. S. CRAFTS AND C. W. CLEARY

TOXICITY OF ARSENIC, BORAX, CHLORATE, AND THEIR COMBINATIONS IN THREE CALIFORNIA SOILS[1]

A. S. CRAFTS[2] AND C. W. CLEARY[3]

INTRODUCTION

IN WEED CONTROL it is often desirable to apply two or more chemicals at the same time. Where, for example, both annuals and deep-rooted perennials occur, arsenic and chlorate combined may be used for complete sterilization. In such cases one must know the reciprocal effects of these reagents in order to use them with any assurance of success. This paper describes experiments designed to show the toxicity of three common herbicides used two and three at a time in three California soils.

TOXICITY STUDIES

Tests on the toxicity of sodium arsenite and sodium chlorate (*2*)[4] and sodium borate (*3*) used separately, in these soils have been published and the technique has been described. Briefly, it consists in growing indicator plants, Kanota oats in this case, in soil cultures in No. 2 cans. The chemicals being studied are added to the air-dry soil, dissolved in sufficient water to bring the soil to its field capacity. The cultures are then seeded and grown for 30 days, at which time the height and fresh weight of the indicator plants are recorded.

In the preliminary toxicity tests (*2, 3*) concentration series were used covering the complete range from 0 to 100 per cent toxic and beyond, so that cultures were included that showed no plant growth even after several croppings. In the present experiments two arbitrary growth levels were selected: the 50 per cent level at which growth was reduced to approximately one-half that of the untreated checks, and the 10 per cent level at which growth was correspondingly reduced to a low value. The concentrations used to produce growth at these two levels were derived from the original toxicity curves, the data from the first runs with the three chemicals being computed in terms of percentage of checks. Table 1 gives the values expressed as parts per million in terms of the air-dry soil. For the borax they have been converted to the hydrous form that contains 47 per cent water by weight.

[1] Received for publication May 8, 1936.

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[4] Italic numbers in parentheses refer to "Literature Cited" at the end of this paper.

In these experiments the chemicals were applied in solution as the sodium salts—that is, sodium acid arsenite, $NaH_5(AsO_3)_2$; sodium tetraborate, $Na_2B_4O_7 \cdot 10H_2O$; and sodium chlorate, $NaClO_3$. These are the forms in which the chemicals are presented on the market and in which, consequently, they are most conveniently purchased for weed control. Other forms of the same toxic elements may readily be converted to this basis if their composition is known.

The letters *A*, *B*, and *C* are used for convenience in expressing results. *A* designates arsenic, expressed as As_2O_3 and applied as sodium acid arsenite; *B* hydrous sodium tetraborate; and *C* sodium chlorate.

TABLE 1

Rates of Application of Arsenic, Borax, and Chlorate Giving 50 Per Cent and 10 Per Cent Growth in Three California Soils

Soil type	Per cent growth	Arsenic (*A*) As_2O_3	Borax (*B*) $Na_2B_4O_7 \cdot 10H_2O$	Chlorate (*C*) $NaClO_3$
		p.p.m. in air-dry soil		
Yolo clay loam	50	300	300	100
	10	540	540	540
Fresno sandy loam	50	45	130	40
	10	140	240	200
Stockton adobe clay	50	100	700	36
	10	200	1,000	120

The plan of the experiments may best be explained in connection with the presentation of data in table 2. In addition to checks receiving only tap water, each soil at the two growth levels received each chemical in four concentrations as shown in the column headed "Rate." A value of 4 in this column represents an application equal to the whole amount required to reduce growth to the level designated. For instance, in Yolo clay loam at the 50 per cent growth level, opposite the rate 4 in the arsenic set, the crop was 16 cm in height and weighed 6.1 grams. This culture received 300 p.p.m. of As_2O_3. In Fresno sandy loam at the 10 per cent level opposite the rate 4 in the chlorate set the crop was 8 cm in height and weighed 0.3 gram. This culture received 200 p.p.m. of $NaClO_3$. The rates, 3, 2, and 1 represent dosages of $\frac{3}{4}$, $\frac{2}{4}$, and $\frac{1}{4}$ of this basic rate respectively. In the first case cited above the dosages were 75 p.p.m., 150 p.p.m., 225 p.p.m., and 300 p.p.m. As_2O_3. Each column of cultures in each chemical set therefore represents a short concentration series consisting of an untreated check and four concentrations, the highest concentration being intended to reduce the growth in the cultures to the particular growth level under consideration.

TABLE 2

TOXICITY OF ARSENIC, BORAX, CHLORATE, AND THEIR COMBINATIONS, AS SHOWN BY GROWTH OF INDICATOR PLANTS

Application		Yolo clay loam				Fresno sandy loam				Stockton adobe clay			
		50 per cent		10 per cent		50 per cent		10 per cent		50 per cent		10 per cent	
Chemicals	Rate*	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.	Ht.	Wt.
		cm	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
Arsenic	0	15	10.5	14	9.6	28	5.4	26	5.0	15	1.5	15	1.8
	1	17	9.3	15	8.0	28	5.0	24	3.2	14	1.0	12	0.8
	2	16	7.6	13	4.6	28	4.5	15	1.2	10	0.7	10	0.6
	3	16	6.9	13	2.7	27	4.0	10	0.6	9	0.5	9	0.4
	4	16	6.1	6	0.6	25	3.3	8	0.4	9	0.5	8	0.3
Borax	0	16	9.3	14	10.0	28	5.4	27	5.2	15	1.4	14	1.6
	1	16	9.9	15	9.7	30	4.9	29	4.0	16	1.3	14	1.1
	2	17	8.9	17	7.6	30	4.3	30	3.3	15	1.1	15	1.2
	3	17	8.1	13	4.0	32	4.2	24	2.0	17	1.2	11	0.6
	4	17	6.4	6	0.9	29	3.0	17	0.7	15	0.9	4	0.1
Chlorate	0	17	10.7	15	9.6	28	5.6	27	4.9	16	1.7	15	1.7
	1	16	6.8	11	2.5	31	4.7	23	2.0	15	1.3	7	0.4
	2	17	5.7	8	1.0	28	3.2	19	1.1	9	0.6	5	0.2
	3	16	5.0	5	0.3	28	3.1	9	0.5	8	0.4	5	0.2
	4	15	4.0	5	0.2	26	2.5	8	0.3	6	0.2	4	0.1
A+B	4+0	16	6.1	6	0.6	25	3.3	8	0.4	9	0.5	8	0.3
	3+1	17	7.0	9	2.0	25	3.1	9	0.4	12	0.8	8	0.2
	2+2	17	7.2	14	3.7	28	3.3	9	0.4	13	0.7	8	0.2
	1+3	18	7.5	12	3.2	30	3.2	13	0.5	14	0.8	8	0.3
	0+4	17	6.4	6	0.9	29	3.0	17	0.7	15	0.9	4	0.1
A+C	4+0	16	6.1	6	0.6	25	3.3	8	0.4	9	0.5	8	0.3
	3+1	15	5.6	6	0.4	28	2.9	8	0.4	10	0.8	7	0.3
	2+2	16	5.0	5	0.4	27	2.5	9	0.4	10	0.6	5	0.2
	1+3	16	4.5	4	0.3	25	2.6	8	0.4	7	0.3	5	0.2
	0+4	15	4.0	5	0.2	26	2.5	8	0.3	6	0.2	4	0.1
B+C	4+0	17	6.4	6	0.9	29	3.0	17	0.7	15	0.9	4	0.1
	3+1	18	8.0	10	2.0	30	3.7	24	1.5	14	1.0	8	0.5
	2+2	16	7.1	13	2.4	30	4.2	23	1.7	15	1.1	9	0.7
	1+3	17	5.9	14	1.7	27	3.1	20	1.4	13	0.8	5	0.2
	0+4	15	4.0	5	0.2	26	2.5	8	0.3	6	0.2	4	0.1
A+B+C	1+2+1	17	7.3	14	3.1	32	5.2	16	1.1	14	0.8	10	0.5
	1+1+2	18	6.4	13	2.2	30	4.0	19	1.0	12	0.9	7	0.4
	2+1+1	18	6.6	14	2.7	29	3.9	11	0.6	11	0.8	9	0.4
	$\frac{4}{3}+\frac{4}{3}+\frac{4}{3}$	18	6.6	14	2.7	30	4.1	16	0.9	12	0.9	10	0.5
Checks†	0	17	10.4	15	10.1	28	5.5	27	5.1	16	1.5	16	1.7

* "Rate" is expressed in quarters of the amount of chemical necessary to produce the desired growth levels; see explanation on page 402.

† Average of 17 replicates.

In the combination sets the three chemicals were used two at a time and three at a time. They were combined in the proportions designated in the "Rate" column. These values refer strictly to the concentrations of the designated chemicals: in the $B + C$ set, $2 + 2$ means that in Yolo

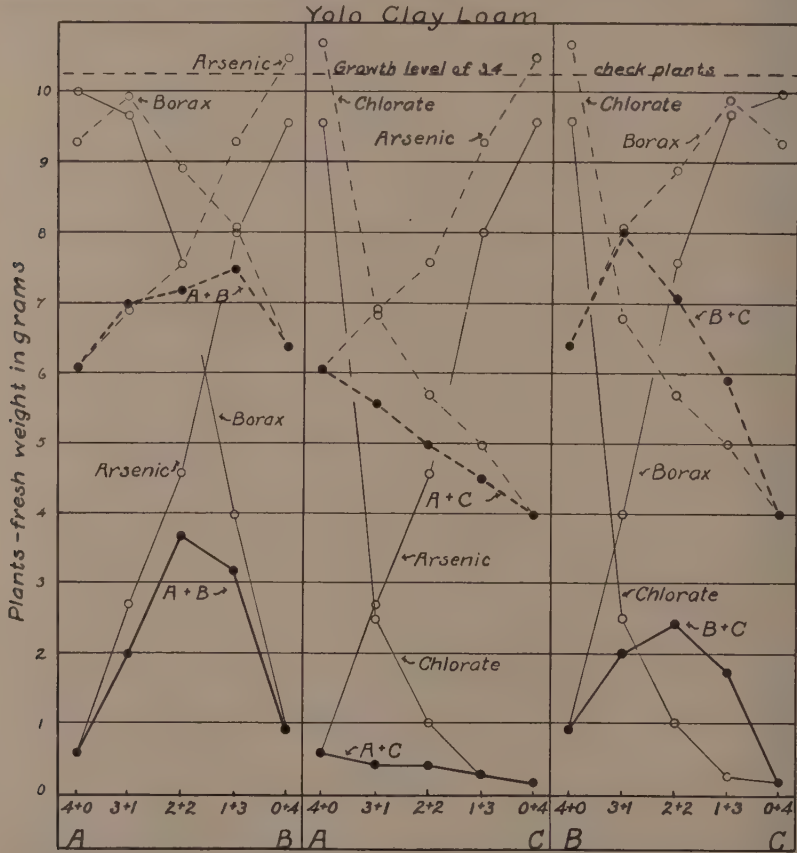

Fig. 1.—Toxicity of arsenic, borax, chlorate, and their combinations used two at a time in Yolo clay loam. Solid lines in lower part of the figure indicate the 10 per cent growth level, and dotted lines in the upper part, the 50 per cent growth level.

clay loam, for example, 2/4 of 300 p.p.m. of borax (table 1) and 2/4 of 100 p.p.m. of chlorate (table 1) were combined at the 50 per cent level. The dosages were therefore 150 p.p.m. of borax and 50 p.p.m. of chlorate respectively, not equal dosages of each. The same rule applied where all three chemicals were used in combination.

In each soil there were 34 different treatments, run in triplicate, and 8 checks for each growth level. The values given in table 2, except the

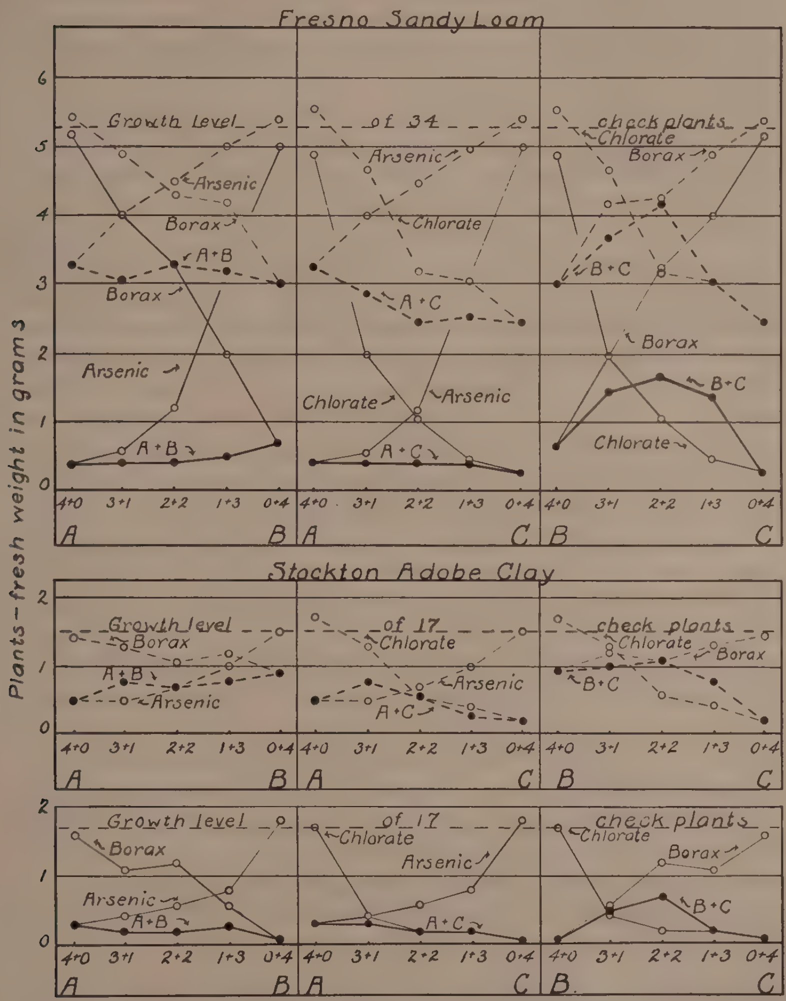

Fig. 2.—Toxicity of arsenic, borax, chlorate, and their combinations used two at a time in Fresno sandy loam and Stockton adobe clay. Solid lines in lower part of the figure indicate the 10 per cent growth level, and the dotted lines in the upper part the 50 per cent growth level.

checks at the end, represent the average of the three replicates. The values for the checks at the end of the table include the 8 unattached checks in addition to the 9 included in the single chemical sets shown above.

To facilitate the interpretation of the data figures 1, 2, and 3 have been prepared. The first two show the toxicity curves for the single chemicals and their combinations when used two at a time; figure 3 shows the relations of the chemicals used singly and used three at a time.

When herbicides are used in combination there are three possible types of response. The effects might be strictly additive. That is, at a given growth level the result of chemical treatment should be the same whether the dosage is all applied as one chemical or another, or as combinations of the two, of such amounts as to total the same in all cases. Considering, for example, the curves in figure 2 for arsenic and chlorate in Fresno sandy loam at the 10 per cent level, it made little difference whether the application was made of 4 increments of arsenic, 3 of arsenic plus 1 of chlorate, 2 of each, 1 of arsenic plus 3 of chlorate, or 4 of chlorate. In all five cases the results were essentially the same.

The second possibility is that the two chemicals might be antagonistic in their action, and the resultant reaction upon the plant might be less from mixtures than from either alone. This is the case with the chlorate-borax mixtures in all three soils.

The third possibility is that the total effect upon plants of the combination treatment might be greater than that expected on the basis of the sum of the individual effects of the two taken alone. This type of response was not observed with any of the mixtures used in these experiments.

There are three types of toxicity curves in figures 1 and 2: straight-line curves such as that for arsenic at the 50 per cent level in the Fresno sandy loam; curves that are concave as viewed from above, such as the arsenic and chlorate curves at the 10 per cent level in Fresno sandy loam; and curves that are convex when viewed from above, as the borax curves in the Yolo clay loam.

The straight-line curve indicates that all increments of a single chemical are of equal value. The concave curves indicate a high toxicity for the first increments and decreasing effectiveness as more are added. Chlorate-toxicity curves are usually of this form if the total dosage approaches the zero growth level. Convex curves indicate low toxicity in the low applications and increasing effectiveness as a lethal dosage is approached.

Evidently the combination curves in figures 1 and 2 are influenced in

practically every experiment by the form of toxicity curves of the two component chemicals. In the Yolo clay loam there is antagonism between arsenic and borax at both growth levels, with toxicity much lower than would be expected on the high-borax side. In the arsenic-chlorate combinations there is in a sense no antagonism, since the curves connecting the two extremes are practically straight lines at both growth levels; but there is considerable difference in the effectiveness of the different increments of each chemical, the first of chlorate being particularly toxic in both cases.

In the borax-chlorate experiment there is distinct antagonism, the combination curve crossing that for chlorate alone, a fact indicating that the borax detracted from the effectiveness at the high-chlorate—low-borax end. This response, though related to the convex form of the borax curve, is more pronounced than would be expected from the results with those two chemicals alone.

In the Fresno sandy loam the borax is much more toxic (table 1) and in combination with arsenic shows no marked reduction in toxicity. Arsenic and chlorate also show straight-line curves for the combinations in this soil. Borax and chlorate again show antagonism with the combination curves crossing the chlorate curves. This same behavior is shown in Stockton adobe clay, where borax toxicity is extremely low. Since it occurs in all three soils it is probably related to the chemicals and relatively independent of the soil type. The arsenic-borax and arsenic-chlorate curves in the Stockton soil are essentially straight lines, a fact indicating that these combinations have little or no antagonistic action in both this and the Fresno soil.

Evidently the combinations used three at a time (fig. 3) are all less toxic than equivalent dosages of the single chemicals; and in some cases, as for example the 10 per cent growth level in Yolo clay loam, toxicities are markedly low. Since this type of mixture has only theoretical interest and is of little practical value, it will not be considered further.

One might judge from the foregoing discussion that these studies have yielded little useful information, since no mixtures of outstanding effectiveness have shown up. Such, however, is not the case. In the first place, it should be pointed out that in the future the principal use of these chemicals in combination will be in soil sterilization, a process that will gain in popularity as agricultural production comes under a higher degree of control. And very probably they will be applied dry wherever possible, for this is the least expensive method.

Among the dry chemicals used in soil sterilization, arsenic comes first in toxicity and retention in available form in the top soil (*1, 2*). In the

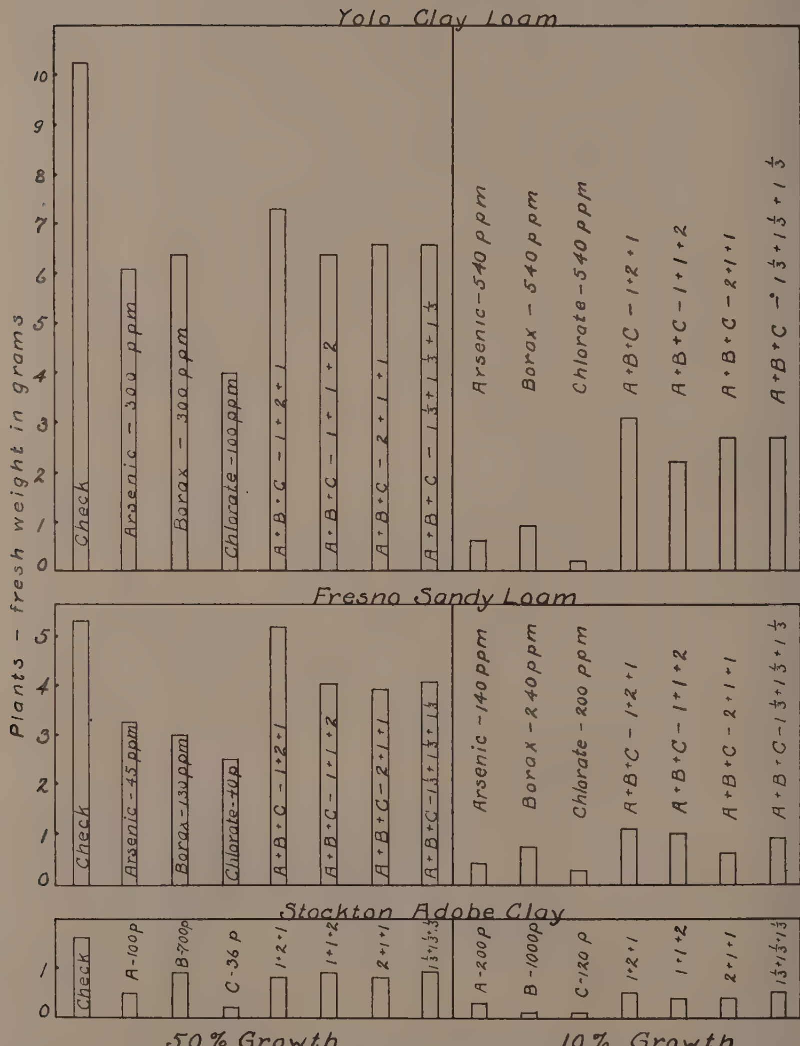

Fig. 3.—Toxicity of arsenic, borax, chlorate, and their combinations used three at a time as shown by growth of indicator plants.

form of the trioxide, however, it is only slightly soluble, and at least one season is required, under California conditions, for enough to become available to give effective sterilization. There is need for an agent that may be combined with it to kill vegetation during the year of application.

Borax, though extremely toxic to many plants when first applied to the soil, soon loses in effectiveness with time and leaching (*3*). It is more firmly retained in the top soil than chlorate and is nonpoisonous to livestock (*3*). Chlorate, being very soluble, is not held against the force of moving water in most soils. It is valuable, in consequence, for treating deep-rooted perennials and will kill annuals during the year of application in California, especially if applied in the late winter or spring.

Considering now the mixtures: arsenic and borax, both being surface sterilants, would have little or no use in combination. Though borax is nonpoisonous and might be substituted for arsenic, it is not satisfactory as a quick killer for annual weeds. In Yolo soils these chemicals are antagonistic.

Chlorate, being soluble and a quick killer, will combine with dry white arsenic to form a very desirable mixture for soil sterilization. Since they are not antagonistic in their action, these reagents may be used in any proportions; and where sufficient chlorate is incorporated, deep-rooted perennials may be eliminated in the process.

On the basis of our data the borax-chlorate combination might seem to hold little promise, since the action of these chemicals was antagonistic in all three soils. Several advantages, however, may be gained by using this mixture. Both chemicals are nonpoisonous as applied in this method; the fire hazard in the use of the chlorate would be practically eliminated; the effects would be considerably more durable than in the use of chlorate alone; and the cost could be materially reduced.

Experiments indicate that colemanite may be used as a substitute for borax (*3*). This fact would place this chemical on a cost basis of about one-tenth that of chlorate, and a very effective mixture of the two could be marketed at a nominal cost. The principal problem is to prescribe the proportions for mixing and the dosages to be used on different soils and under various climatic conditions.

The shape of the toxicity curves of borax and chlorate indicates that the most effective increments of chlorate are the first, whereas the higher applications of borax have the most pronounced effect. The combination curves indicate, furthermore, a high antagonism where little borax was combined with much chlorate. Evidently, therefore, in combining these two chemicals one should use a minimum effective dosage of chlorate and should add borax as the need is indicated by the soil type and local

conditions. From table 1 little chlorate is required to reduce growth 50 per cent. In two soils less borax than chlorate is needed to lower it from 50 per cent to 10 per cent, and in the Stockton soil less than four times as much borax as chlorate is required. Considering the 1 to 10 differential in price, it seems logical to use chlorate through its range of maximum effectiveness and then to add borax enough to finish the destruction. With the added residual effect of the borax, this combination should prove economical. It is excelled only by arsenic and chlorate, a mixture which has limited use because of its poisonous nature.

DISCUSSION

The foregoing considerations indicate the use that may be made of greenhouse technique in building a body of information upon which to base an interpretation of field results. The limitations of the method should also be pointed out. As several years of experience have shown, the toxic concentrations of the various chemicals studied are not absolute but depend somewhat upon growth conditions of the indicator plants. Borax and chlorate are evidently absorbed and translocated in plants and tend to accumulate in the leaves. The toxicity of these reagents is affected, therefore, by conditions determining rates of absorption and water loss. In addition, toxicity is rapidly reduced during the initial stages of any experiment of this type; and although this loss can be shown only by comparing successive crops, it is going on from the time the first crop is planted. Since toxicity loss varies in rate with different chemicals and under different environmental conditions, comparative studies with two or more chemicals are limited in accuracy. For such reasons the concentrations required to reduce growth to certain fixed levels may not always be the same, and with the best of judgment the worker may miss the desired points. This was the case in the Yolo soil, where both the arsenic and borax concentrations used failed to bring growth to the 50 per cent level, while the chlorate concentration took it below this line. Similar discrepancies can be observed in the other two soils, which indicate the general nature of the disturbing factors. Though these discrepancies interfere somewhat with the results, the general responses are so apparent that their value is little depreciated. The convenience and adaptability of the method far outweigh its drawbacks as is indicated by the conclusions drawn.

These same factors that limit the accuracy of the greenhouse method affect the results of field applications. Chemical treatments for soil sterilization are subject not only to such obvious factors as rainfall, temperature, soil type, and species susceptibility, but to all those complex

relations that determine the crop-producing power of soils and their ability to fix and retain solutes against the force of moving water. For the present the best that can be done in determining the behavior and effects of herbicides in soils is to study, by the empirical methods described, the growth of plants in the treated soils. Such studies are providing abundant information, sufficiently accurate to aid materially in the design and ultimate interpretation of field-plot studies.

SUMMARY

In the greenhouse experiments described, sodium arsenite, hydrous sodium tetraborate, and sodium chlorate are used singly and in combination to reduce growth of indicator plants.

Concentrations of these three chemicals required to reduce growth to the 50 per cent level and to the 10 per cent level in Yolo clay loam, Fresno sandy loam, and Stockton adobe clay were derived from previously published data.

In the present experiments, check series were set up in each soil, the individual chemicals being applied in increments of $\frac{1}{4}$, $\frac{2}{4}$, $\frac{3}{4}$, and $\frac{4}{4}$ of that required to reduce growth to the specified level. Each such set, constituting a short concentration series, was used as a basis for comparing the combination treatments.

In experiments combining the chemicals two at a time, they were applied in proportions of $4 + 0$, $3 + 1$, $2 + 2$, $1 + 3$, and $0 + 4$. The chemicals used three at a time were combined in the proportions of $1 + 2 + 1$, $1 + 1 + 2$, $2 + 1 + 1$, and $\frac{4}{3} + \frac{4}{3} + \frac{4}{3}$.

Arsenic and borax showed antagonistic reaction in Yolo clay loam at both the 50 per cent and the 10 per cent growth levels.

Arsenic and borax toxicities were additive in Fresno sandy loam and Stockton adobe clay.

Arsenic and chlorate toxicities were additive in all three soils at both growth levels.

Borax and chlorate showed antagonistic reactions in all three soils at both growth levels.

The combination of the chemicals used three at a time are of only theoretical interest and provide no practical information.

In the practical application of these chemicals the arsenic-borax combination would find little use.

Sodium chlorate and white arsenic applied dry, form a very useful mixture for soil sterilization. As shown by the greenhouse experiments, there is no indication of loss by antagonism in their reactions.

In the use of borax and sodium chlorate in combination for soil sterili-

zation the antagonism in their action can be reduced to a minimum by using the lowest effective dosage of chlorate and adding enough borax to complete the destruction of the vegetation.

The borax-chlorate combination for soil sterilization has the advantage of being practically nonpoisonous; and the use of the borax, besides reducing the fire hazard of the chlorate to a low level, provides a residual effect that lowers the probability of reinfestation by seedlings.

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